2. The FAFP in the orographic region of the storm is approximated by the maximum precipitation depths in the nonorographic region, as long as the same atmospheric forces are involved at each location.

3. Estimates of the FAFP based on assumptions 1 and 2 are better for small rather than intermediate or large area sizes.

7.3.1.3 Module 2. This module uses an isohyetal analysis of the precipitation data to evaluate the free air forced component of precipitation. Inherent in the use of this module is the existence of an isohyetal analysis based on adequate precipitation information and prepared without undue reliance on normal annual precipitation or other rainfall indices which may induce a spurious correlation between the precipitation amounts and topography. In addition, there are five other concepts underlying this module. These are:

1. One or more than one level of LOFACA may exist in the orographic part of a storm. When more than one storm center is contained in a given area category, the lowest level of LOFACA found is used for that area size.

2. LOFACA exists when there is a good correlation between some isohyet and elevation contours.

3. Upsloping and triggering (F- and B-type correlations) are of equal significance in determining the percentage of precipitation above LOFACA which is terrain forced.

4. For an orographic storm (centered in th orographic portion of the region), the larger the nonorographic portion becomes (in relation to the total storm area), the more likely that the observed largest rainfall amount in the nonorographic portion (as represented by DADFX) is the "true" upper limit to FAFP in the orographic part of the storm.

5. Estimates of FAFP using the above assumptions are better at intermediate and large rather than small area sizes.

7.3.1.4 Module 3. This module makes use of the meteorological analysis and the evaluation of the interaction of dynamic mechanisms of the atmosphere with terrain to estimate the FAFP. There are seven basic concepts underlying the use of this module. These are:

1. Estimates of FAFP made using the techniques of this module may be of marginal reliability if the storms considered are those producing moderate or lesser precipitation amounts.

2. A variety of storms exist, each one of which has an optimum configuration for producing extreme precipitation.

3. The more closely the atmospheric forcing mechanisms for a given storm approach the ideal effectiveness for that type of storm, the larger the effectiveness value (P_a) for that storm becomes.

4. The FAFP is directly proportional to the effectiveness of atmospheric forcing mechanisms and inversely proportional to the effectiveness of orographic forcing mechanisms.

5. If the effectiveness of the orographic forcing mechanisms is of opposit sign to the effectiveness of the atmospheric forcing mechanisms and o equal or larger magnitude, little or no precipitation should occur.

6. The FAFP of storms of record is arbitrarily limited to no more thar 100 percent of the maximum precipitation depth for the area/duratior category under consideration.

7. Estimates of FAFP using the above assumptions are better at large rather than at intermediate or small area sizes.

7.3.1.5 Module 4. A basic assumption underlying the use of module 4 is that better results can be obtained by combining information; i.e., averaging the percentages obtained from the isohyetal analysis with the meteorological analysis and those obtained from analysis of the precipitation observations with the meteorological analysis. Better estimates are produced by averaging when there is little difference in the expressed preference for any one of the techniques or sources of information and, also, when the calculated percentage of FAFP from each of the modules exhibits wide differences.

Little is to be gained from use of the averaging technique over estimates produced by one of the individual analyses of modules 1, 2, or 3 when:

1. There are large differences in the expressed preference for the techniques of one module.

2. The sources of information for one of the individual modules is definitely superior.

3. The calculated percentages among the modules are in close agreement.

7.4 Methodology

The SSM was developed in a modular framework. This permits the user to consider only those factors for which information is available for an individual storm. A MAIN FLOWCHART of the SSM is shown in figure 7.2.

The MAIN FLOWCHART gives the user an overview of the SSM. Modules 1, 2, and 3 are designed to use the first three information sets mentioned in section 7.3 as indicated by the remarks column at the left side of the flowchart. A decision must be made initially for any storm and category as to which modules can be appropriately used, module 1, 2, or 3. The decision is based on a minimum level of acceptability of the information required by the module in question. The decisions are formalized for each of these three modules in module 0. The heart of the SSM procedure is module 5 where documentation is made of the SSM process, thereby permitting traceability of results. Though module 5 can be reached on the flowchart only after passing through each of the other modules, it is recommended that the steps in each module be documented in the record sheet of module 5 as the analyst proceeds. Transposition and moisture maximization of the index value of precipitation follows the completion of the SSM and will be discussed in chapter 8.

7.4.1 Module Flowcharts

There is a flowchart for each module. These were developed to aid the analyst in following the procedures in the SSM.

7.4.1.1 Module 0 Procedure (fig. 7.3). It is important in this module to decide on the adequacy of the available data. The results of this assessment are entered in column D of figure 7.8. The following rules concerning criteria are used:

1. For modules 1, 2, or 3, if there are no data available for the given technique (module), assign 0 to column D.

2. If the data are judged to be highly adequate, assign a value of either 7, 8, or 9, where 9 is the most adequate.

3. If the quantity, consistency, and accuracy of the information are judged to be adequate, assign a value of either 4, 5, or 6 to column D.

4. If the input information are judged as neither highly adequate, adequate, or missing, a value of either 1, 2, or 3 must be assigned to column D. A value of 1 is the lowest level of adequacy consistent with affirmative responses to questions 3, 5, and 7 in module 0.

An evaluation of a technique is not appropriate when there is insufficient information available for it to be used. Assigning an effective value of zero to column D under these circumstances eliminates the possibility.

The Glossary of Terms provides all required information needed to give numerical values to the five variables in the first step of the module 0 procedure. Note: In this module and in modules 1, 2, and 3, the connector symbol (C) applies only within the given module; i.e., when one is sent to a connector symbol it is always the one that is found in <u>that</u> module.

The following questions need to be answered in this module:

Q.1. Is PC equal to or greater than 0.95?

Q.2. Is there a MXVATS for an area size equal to or less than 100 mi^2 on the Pertinent Data Sheet for this storm?

Q.3. Are the quantity, quality, and distribution of the nonorographic observations sufficient to select a reliable value for RNOVAL?

Q.4. Is an isohyetal analysis available?

Q.5. Is the isohyetal analysis reliable?

Q.6. Is a reliable isohyetal analysis easily accomplished?

Q.7. Are the meteorological data sufficient to make a reliable estimate of P_a and A_o?

Q.8. Is RNOVAL equal to zero?

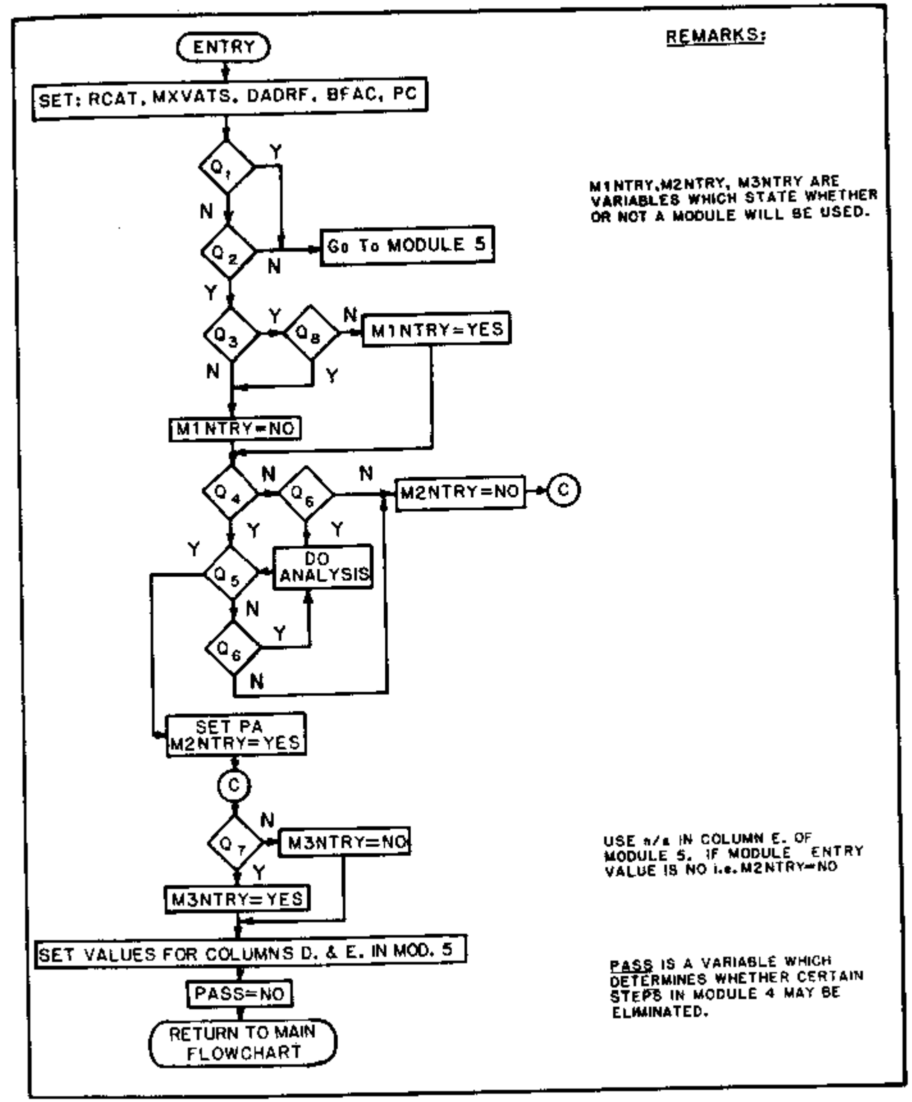


Figure 7.3.--Flowchart for module 0, SSM.

303

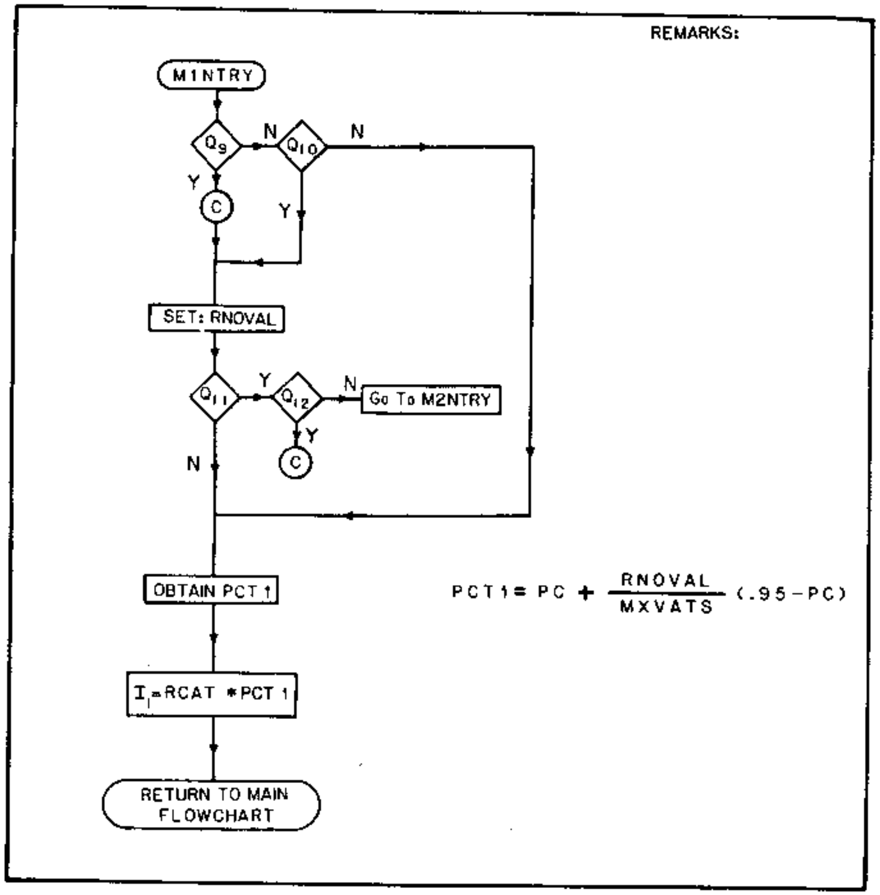


Figure 7.4.--Flowchart for module 1, SSM.

7.4.1.2 Module 1 Procedure (fig. 7.4). This module comes closer than any other in estimating a value for FAFP based on observed precipitation data. The key variables RNOVAL and MXVATS are based on direct observation, even though in some circumstances uncertainty surrounds the accuracy of these observations. The

actual values selected depend on the placement of the OSL (sec. 3.2.1) in the vicinity of the storm under consideration. Additionally, an analytical judgment must be made concerning the storm mechanism that resulted in MXVATS and RNOVAL. If there is more than one storm mechanism involved in the storm, the value selected for RNOVAL must result from the same mechanism that produced MXVATS.

The following questions are asked in module 1:

Q.9. Is this the first time in this module for this storm?

Q.10. Has the analyst just arrived here from module 4 to do a review?

Q.11. Is RNOVAL equal to MXVATS?

Q.12. Is a review of the data and assigned values for the variable needed?

If it is a good assumption that RNOVAL will usually be observed at a lower elevation than MXVATS, then there is a bias toward relatively large values for PCT1 in relation to the other percentages from the other modules, since total or cumulative precipitable water usually decreases with increasing elevation. The viability of PCT1 depends on the density of good precipitation observations on the date the storm occurred.

7.4.1.3 Module 2 Procedure (fig. 7.5). In this module, the average depth of precipitation for a given area-duration category is conceived of as a column of water composed of top and bottom sections (where the bottom section can contain from 0 to 95 percent of the total depth of water). The limit to the top of the bottom section is set by the parameter LOFAC. The bottom section is conceived to contain only a minimum level of FAFP for the storm. The top section contains precipitation that results from orographic forcing, and perhaps additional atmospheric forcing. The percent (if any) of the top section that results from atmospheric forcing is determined by the F-type and 8-type correlations. The value computed for LOFAC is sensitive to the accuracy of the isohyetal analysis for the storm. This sensitivity must be taken into account when evaluating module 2 procedures in column E of module 5.

The procedure in which the precipitation is divided into two sections, is represented also in the expression for PCT22, which may be rewritten as:

$$PCT22 = PCT2\left(1 - \frac{LOFAC}{MXVATS}\right) + \frac{LOFAC}{MXVATS}$$

There are three terms on the right-hand side of the above equation. The rightmost of these terms is the minimum level of FAFP for the whole column expressed as a percent of the total and is the bottom section of the idealized column described above. The product of the first two terms on the right-hand side of the equation describes the top section of the idealized column, where PCT2 is the percent of the top section arising from atmospheric forcing and the second term is the depth of total precipitation minus the minimum level of FAFP expressed as a percent.

LOFACA is set to zero and LOFAC becomes zero when a good correlation cannot be found between any of the isohyets and the elevation contours upwind of the storm center. Zero is the numerical value that is appropriate for a minimum level of FAFP for the storm. Here it is assumed that the bottom section of the idealized

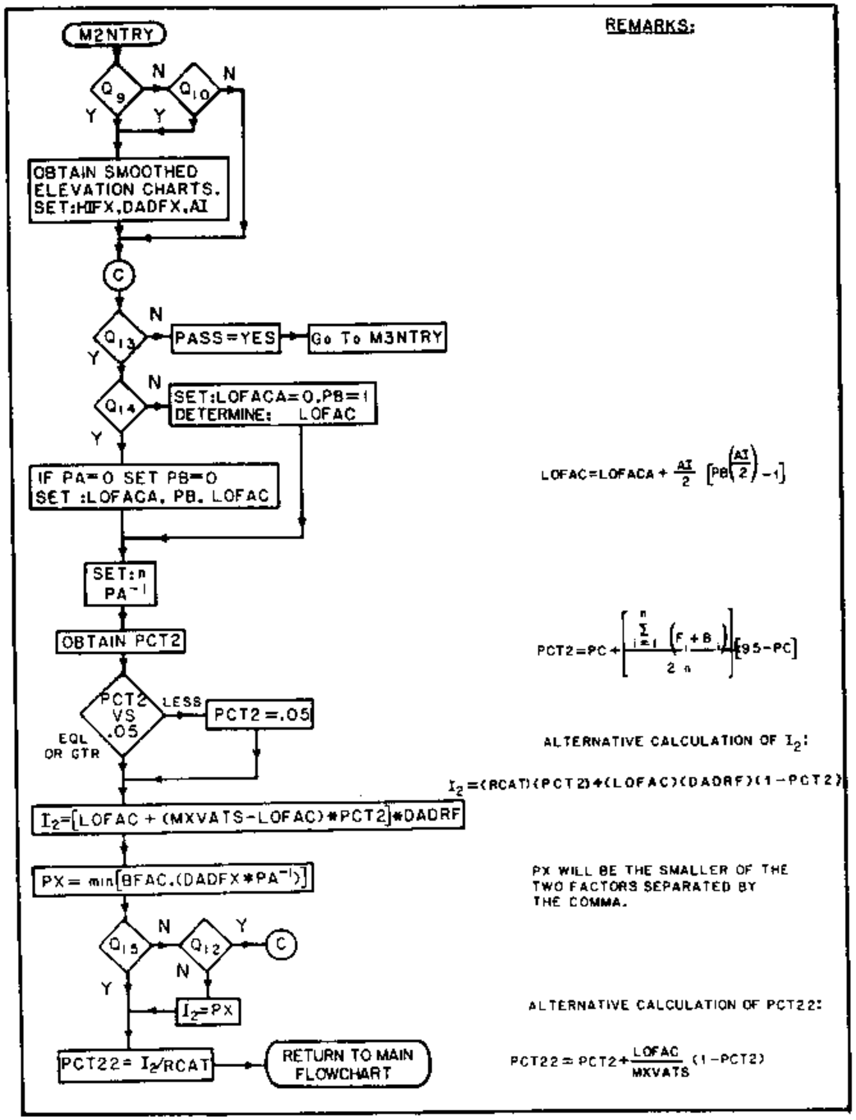


Figure 7.5.--Flowchart for module 2, SSM.

column is empty (minimum level of FAFP = 0), and both F-type and B-type correlations will determine the appropriate level of FAFP for the storm. The F and B correlations, to properly establish the appropriate FAFP, are determined nearby and upwind from the storm center.

As in module 1, an analytical judgment must be made on storm mechanism. In module 1, it was required that MXVATS and RNOVAL are the result of the same dynamic process. In module 2, it is necessary to determine that RNOVAL and HIFX are the result of the same atmospheric forces (storm mechanism).

The following questions are asked in module 2:

Q.9. Is this the first time in this module for this storm?

Q.10. Has the analyst just arrived here from module 4 to do a review?

Q.12. Is a review of the data and assigned values for the variable needed?

Q.13. Can it be determined which isohyetal maxima control(s) the average depth for the category selected?

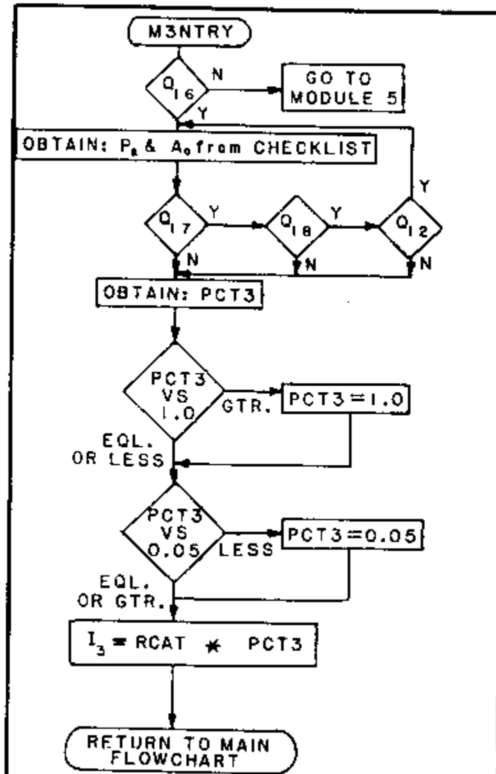
Q.14. Is there good correlation between some isohyet and the elevation contours in the orographic part of the storm near the storm center?

Q.15. Is I_2 less than or equal to PX?

A feature of module 2 not to be overlooked is the consequence of a negative response to question 15 accompanied by a negative response to question 12. In this case an arbitrarily defined upper limit is set on PCT22 and I_2. The upper limit will be the smaller of two numbers. The selection of BFAC as one of these numbers is obvious when one considers that orographic forcing may be either positive or negative. The second factor is a consequence of the concept that the larger PA becomes, the more likely the second factor represents the true level of FAFP, since with a large value of PA the largest observed rainfall amount in the nonorographic portion is more likely to represent a true upper limit.

LOFAC is always a number equal to or slightly less than LOFACA. This is so because it is possible that the minimum level of FAFP is reached before the arbitrarily set analysis interval allows it to be "picked up." It is reasoned that the larger the area "occupied" by the LOFACA isohyet in the nonorographic part of the storm, the more likely that the analysis interval has "picked up" the described depth. When there is no nonorographic portion to the storm, the parameter PB, used to set a value for LOFAC, becomes undefined (see definition of PB). Consequently, in the module 2 FLOWCHART it must be determined whether a nonorographic portion of the storm exists when there is an affirmative response to question 14. If so, a reasonable value for PB is zero. The consequence of a negative response to question 14 is that LOFACA must be zero. Regardless of whether or not a nonorographic part of the storm exists, LOFAC must not be less than zero and this is ensured by setting PB equal to 1.

7.4.1.4 Module 3 Procedure (fig. 7.6). This module uses meteorological and terrain information to evaluate an appropriate level of FAFP. This is accomplished through evaluation of P_a and A_o.



P_a CHECKLIST					
Cat. Data	Parameter	A (√)	B .05-.95	C 1-3	D B*C
Surface	Iso.Ptn. Fronts Waves Sq.Ln. Other				
Upper Air	PVA/SW Cutoff Blocking JetStm Other				
Rawinsonde	Stability Shear Other				
Satellite	Diver. Merger MCC Other				
Radar	LEWP Merger Others				
Other					
Duration (%)					
Totals =					
P_a = Total D/Total C =					

REMARKS

$$PCT3 = PC + \frac{P_a}{P_a + A_o}(.95 - PC)$$

A_o CHECKLIST				
Parameter	A Phys. Val.	B 0-±.95	C 1-3	D B*C
Inflow Direct				
Inflow Speed				
Gradient of Elevation				
Stability				
Other				
Duration (%)				
Totals =				
A_o = Total D/Total C =				

LEGEND

PVA = Positive Vorticity Advection
MCC = Mesoscale Convective Complex
LEWP = Line Echo Wave Pattern

Figure 7.6.—Flowchart for module 3, SSM.

The following guidelines are provided to aid in the evaluation of P_a on the checklist given in the flowchart (fig. 7.6):

1. Use column A to indicate (by a checkmark) the presence of one or more features which infer positive vertical motion, or which may contribute toward an efficient storm structure.

2. Take as a basis for comparison an idealized storm which contains the same features or phenomena that were checked off in column A and indicate in column B, by selecting a number between 0.05 and 0.95, the degree to which the effectiveness of the selected actual storm features/phenomena (in producing precipitation) approaches the effectiveness of the same features/phenomena in the idealized storm. Where more than one feature/phenomenon is selected for a given category of meteorological information, it is the aggregate effectiveness which is considered and recorded in column B.

3. Repeat steps 1. and 2. for each category (surface, upper air,..., others) of meteorological data.

4. If the quantity and quality of the information permits, the degree of convective-scale forcing may be distinguished from forcing due to larger scale mechanisms. If convective-scale forcing predominates for some area/duration categories and larger scale forcing at others, then the value assigned in column B may vary by area/duration category; i.e., the same effectiveness value may be different for each category of a given storm.

5. In column C an opportunity is given to assign one category a greater influence on P_a in relation to the others by assigning weighted values. For each applicable category the value in column D is the product of columns B and C. P_a is obtained by dividing the total of column D by the total of column C.

6. Meteorological data categories, for which there is not sufficient information from a particular storm, are disregarded in P_a calculations for that storm.

7. When effectiveness changes with the selected duration, the resulting value in column B is weighted by duration; this process is to be distinguished from the weighting mentioned in (5) above.

A_o is a measure of the effectiveness of the orographic forcing effects. The following guidelines are used to aid in evaluating A_o:

1. Indicate in column A the value (in physical units) for the first five parameters. If any of these parameters change significantly during the duration category selected, indicate in the duration box the percent of time each of the values persists. To obtain the largest value in column B (largest effectiveness) observe the joint occurrence of tightly packed isobars (high wind speed) perpendicular to steep slopes for 100 percent of the duration category selected. Another way to look at this is to combine the first three parameters into a vertical displacement parameter, W_o, from the formula $W_o = V * S$, where V is the

component of the wind perpendicular to the slopes for the duration being considered in kt and S is the slope of the terrain in ft/mi. The effectiveness of W_o is then compared with an idealized value representing 100 percent effectiveness. The measured steepness of the slopes in the CD-103 region depends on the width across which the measurement is made. For a small distance (less than 5 mi.) a value of 0.25 is about the largest to be found, while for a large distance (greater than 80 mi.) a value of 0.06 is about the largest. A component of sustained wind normal to such slopes of 60 kt is assumed to be about the largest attainable in this region. Therefore, a W_o of 15 kt for small areas and of 3.5 kt for large areas are the values which would be considered highly effective.

None of the orographic storms studied occurred in places where the measured steepness of the slopes came near to the values just mentioned. Consequently, the vertical displacements observed for small areas were from .02 kt up to near 2 kt and proportionally smaller for the larger areas for these storms. Therefore, the effectiveness value used in the top box in column B was scaled to the values observed in the storms of record; i.e., a W_o of close to 2 kt was considered highly effective for small areas.

The inflow level for the storm is assumed to be the gradient wind level, and it is further assumed that the surface isobaric pattern gives a true reflection of that wind; i.e., the direction of the inflow wind is parallel to the surface isobars and its speed proportional to the spacing of the isobars as measured at the storm location. When rawinsonde observations are available in the immediate vicinity of the storm, they are used as the primary source of information for wind direction and speed.

When there is a sufficiently large number of wind observations, the average values of direction and speed are used for the duration considered. If the level of wind variability is large for the duration considered, the representativeness of the data is scored low in column C of module 5.

The fourth parameter, stability, must be considered in combination with the first three or W_o. Highly stable air can have a dampening effect on the height reached by initially strong vertical displacement (and consequently, the size to which cloud droplets can grow). In a highly unstable condition, vertical displacements of less than 2 kt can, through buoyancy, reach great height, thereby producing rainfall-sized droplets. The effectiveness value for stability is placed in the second box from the top in column B. Weighted values corresponding to the two top boxes of column B are placed in the two top boxes of column C to reflect the combined effects of W_o and stability; i.e., in the case where instability causes moderately weak displacements to grow, the stability "effectiveness" would be weighted strongly (given a 3) and the combined first three parameters weighted weakly (given a 1).

Entries in the other considerations box (for example, the shape of terrain features which may cause "fixing" of rainfall) need not be considered as dependent on the first four parameters.

2. The value for A_o is then obtained in the same manner as described in guideline 5 for P_a.

3. When evidence indicates that the orographic influence is negative; i.e., taking away from total possible precipitation, the values in column B are made negative and when the conditions are borderline between positive and negative, they are made zero. Negative orographic influence, when occurring in a storm where the atmospheric forcing approaches its conceptually optimum state, may cause some category values of PCT3 to exceed 1.0 resulting in FAFP larger than the total storm average depth for that category. The conventions of module 3, however, do not permit values of PCT3 to exceed 1.0.

4. The remarks section of module 5 should be used to document where the elevation gradients (ΔZ) were measured. For small areas, this would typically be at a point upwind of the largest report/isohyet. For larger areas, the average value from several locations may be used, or if one location is representative of the average value, it alone may be used. Sometimes the gradient is measured both upwind and downwind of the storm center (where inflow wind is used) if the vertical wind structure is such that a storm updraft initiated downwind may be carried back over the storm location by the winds aloft to contribute additional amounts to the "in place" amounts.

The overriding importance of applying this module only to major storms cannot be overstressed. The consequence of "running through" a frequently observed set of conditions is that, by definition, the values for both P_a and A_o will have to be quite small. When both parameters are small (less than about .4) a sensitivity study (not included here) showed that small differences in the values assigned to P_a and A_o (the independent variables) would produce large differences in the value of the dependent variable (PCT3). However, it does not follow that the definition of P_a which permits a lower limit of zero is incorrect. A storm can reasonably be postulated in which the extreme amounts were traceable to exceptional orographic forcing and, thus, both terms would not be small (PCT3 in this case is 5 percent). Not only are "infinite" values for PCT3 removed by the FLOWCHART constraints, but a value of zero in the denominator of the ratio $P_a/(P_a + A_o)$ is a violation of the concept that if the orographic forcing negated the atmospheric forcing, no matter how large, little or no precipitation should occur.

The "model" envisioned in module 3 (as distinguished from the "model" of module 2 just discussed) follows from the concept that FAFP is directly proportional to the effectiveness of atmospheric forcing and inversely proportional to the effectiveness of the orographic forcing mechanisms. The rate at which an imaginary cylinder fills up (whose cross-sectional area is the same as the area category being used) is directly proportional to the condensation rate producing the precipitation which falls into the cylinder. The paramount factor determining the condensation rate is the vertical component of the wind resulting from both atmospheric (P_a) and orographic (A_o) forcing.

The following questions are asked in this module:

Q.12. Is a review of the data and assigned values for the variable needed?

Q.16. Does there exist, or is there sufficient information available to construct, a map of where at least 1 in. of precipitation did or did not occur for this storm?

Q.17. Is A_o less than zero?

Q.18. Is (are) the storm center(s) incorrectly located on the terrain map?

The remaining portions of the module 3 FLOWCHART, not discussed above, are simple and straightforward.

7.4.1.5 Module 4 Procedure (fig. 7.7). It is not contemplated that a computer program will be coded from the MAIN or MODULE FLOWCHARTS because the determination of the appropriate PCT's and I's is done easily manually. There is no real requirement for the variable PASS to be in the module 4 FLOWCHART. It is included only to make it obvious that the first part of the FLOWCHART should be skipped when returning to module 4 from a review of data in modules 1 and 3. The purpose of this module is simply to create two additional indices of FAFP on the assumption that an averaged value may be a better estimate than one produced in modules 1, 2, or 3.

A preliminary test of the SSM by six analysts each using six different storms showed that it was quite rare that one analyst would select a high (low) value for a PCT when other analysts were selecting low (high) values given that the interval range was the one shown in the right-hand remarks section of the module 4 FLOWCHART. Thus, a review is required of relevant information when an average percentage is to be created from individual percentages differing by two intervals.

PCT1 was not averaged with PCT2 because modules 1 and 2 conceive of the idealized column of precipitation representing the average depth for a given area-duration category in different ways; i.e., there is no minimum level of FAFP considered in module 1.

The following questions are asked in this module:

Q.12. Is a review of the data and assigned values for the variable needed?

Q.19. Is I_5 less than or equal to PX?

Those concepts of the module 4 FLOWCHART not discussed above are straightforward.

7.4.1.6 Module 5 Documentation (fig. 7.8). It should be noted again that even though the MAIN FLOWCHART shows that module 5 is not used until module 2 and/or module 4 have been completed, this was done only to keep the diagramming of the MAIN FLOWCHART and the MODULE FLOWCHARTS relatively uncluttered by variables not related to the task at hand. Even though documentation can await completion of module 2 and/or module 4, it is preferable to document the value assigned to a variable as soon as it is determined.

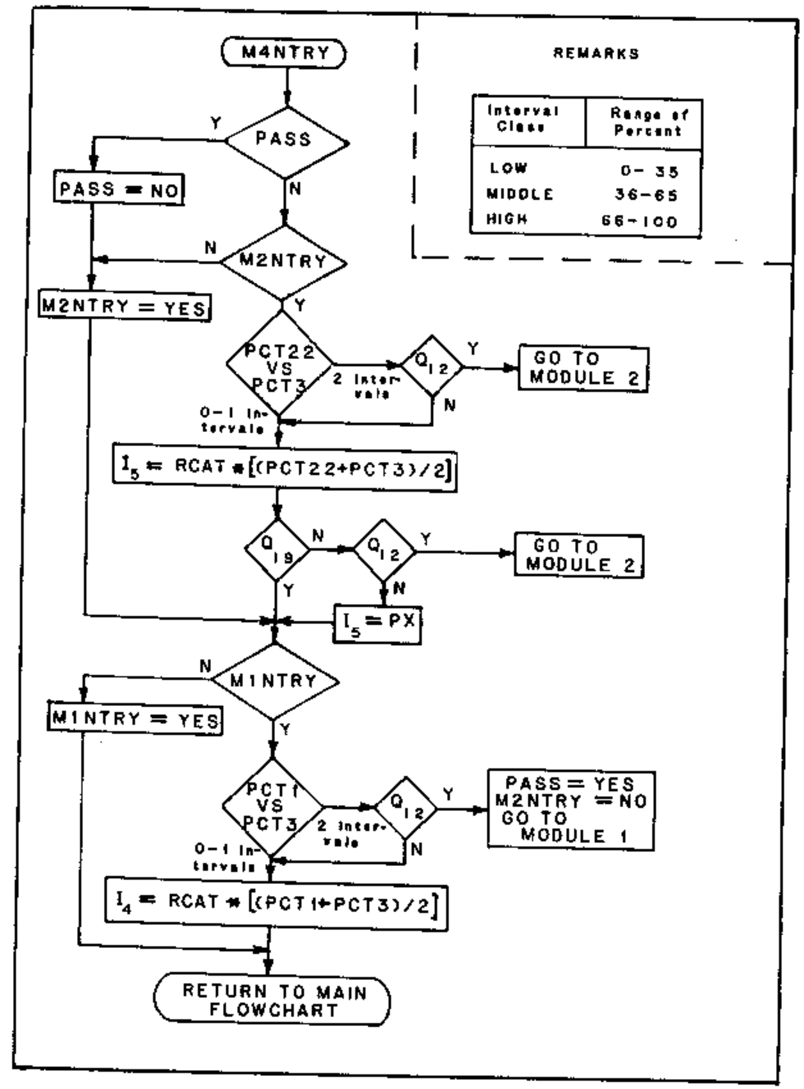


Figure 7.7.—Flowchart for module 4, SSM.

DOCUMENTATION AND INDEX SELECTION

STORM ID/DATE, REMARKS:

MODULE	PARAMETER	VALUE	EVALUATION SCALE: COL.D 0-9; COL.E 1-9 MODULES 1-3: COL.F: IS THE SUM OF COLS. D&E. COL.D: HOW ADEQUATE IS THE INPUT INFORMATION FOR THE REQUIREMENTS SET BY MODULE'S TECHNIQUE. COL.E: HOW LIKELY IT IS THAT THIS TECHNIQUE WILL ESTIMATE THE CORRECT INDEX VALUE BASED ON ITS ASSUMPTIONS? FOR MODULE 4 SEE SELECTION RULE. OVERALL RULE: SELECT INDEX VALUE WITH LARGEST COL. F SCORE. LARGEST SUBSCRIPT BREAKS TIES.			
			REMARKS	D	E	F
Ø	CATEGORY RCAT BFAC MXVATS DADRF PA PC					
1	RNOVAL PCT1 I_1					
2	AI LOFACA PB LOFAC HIFX DADFX PA^{-1} PX $\sum^{n}(F_i+B_i)$ PCT2 I_2 PCT22					
3	COLUMN	A | B | C				
	INFLOW DIR.					
	INFLOW SPD.					
	GRAD. ELEV.					
	W_0					
	STABILITY					
	A_0					
	SURFACE					
	UPPER AIR					
	RAOB					
	SATELLITE					
	RADAR					
	P_a					
	PCT3					
	I_3					
4	(PCT22 + PCT3)/2					
	I_5					
	(PCT1 + PCT3)/2					
	I_4		RETURN TO MAIN FLOWCHART			

Figure 7.8.—Documentation form for SSM, module 5.

Values were assigned to column D during the review in module 0. This was necessary in the evaluation of the adequacy of data for application of modules 1, 2, and 3 to a particular storm. After completion of the first four modules, it is appropriate to review the values assigned for the adequacy of the data. In some cases, changes in values assigned to column D for some modules are appropriate. Any changes in values assigned in column D should be documented.

Assigning of values to columns E in module 5 involves subjectivity which must be the case because the "correct" value cannot be known and, hence, there is no way to know which of the various techniques used produces "correct" results most frequently. After the storm has been evaluated in each of the modules, all the information is available to assign a value for column E for modules 1 through 3. At this point, the value assigned to column E results from answering this question: For the type of storm selected and for the area/duration category chosen, what is the degree of confidence (i.e., how likely is it) that the particular technique (based on the validity of the assumptions underpinning it) will produce the "correct" result? The scheme for assigning values to column E is:

1. For modules 1, 2, and 3, if confidence is high, assign a value of either 7, 8, or 9 (9 being the highest of all) to column E.

2. If confidence is low, assign a value of either 1, 2, or 3 (where 1 is lowest, zero is not valid).

3. If the level of confidence is other than high or low, you must assign a value of either 4, 5, or 6.

4. If the entry value for the module under consideration is 0 in column D, an entry of n/a is made in column E and a value of zero used when calculating a column F.

5. It is unnecessary to evaluate columns D and E separately for module 4. Values to be assigned in column F for I_4 and I_5 can be determined from the following:

		Overall preference (difference in values assigned column F)		
		Little (0-2)	Some (3-5)	Strong ($\geq$ 6)
Level of agreement between modules (difference in index percentages)	Little ($\geq$ .31)	A	B	B
	Some (.16 - .30)	A	AB	B
	Large (0 - .15)	A	A	B

Where:

A = use the higher of the values from column F for I_4 or I_5.
B = use the lower of the values from column F for I_4 or I_5.
AB = use either the higher or the lower value from column F for I_4 or I_5.

Obviously, the scheme is designed to permit selection of I_1, I_2 or I_3 when there is a strong preference for one of them and to select I_4 or I_5 when there is little overall preference. In the case where there is some preference for a given module and some agreement between the index values generated therefrom, the analyst must make a decision as to which index is to be preferred. The range of values used to represent index agreement categories was based on values actually selected in a test involving six different analysts working with six different storms.

The final value selected for FAFP is determined by the largest value in column F. If the same value has been computed for more than one index value, the index with the largest subscript is selected (I_2 over I_1, I_3 over I_2).

7.5 Example of Application of SSM

One of the most critical storms for determining the PMP in the CD-103 region occurred at Gibson Dam, MT on June 6-8, 1964 (75). Figure 7.9 shows the completed module 5 worksheet for this storm for the 24-hr 10-mi^2 precipitation. The final percentage selected for this storm was 61 percent for PCT5. This gave an FAFP of 9.1 in.

7.6 Application of SSM to this Study

The SSM was used in this study to estimate FAFP for just one category, 10 mi^2 and 24 hr. This category was selected as the key (index) category for this study for several reasons. The first reason relates to area size. In determination of the effects of orography on precipitation, it is easiest to isolate these effects for the smaller areas. In addition, if larger area sizes were used, the determination of the orographic effects for computation of the final PMP values would have been very complicated. At some transposed location, the increase in precipitation as a result of orographic effects for a very small area can be determined with little ambiguity. If a larger area (e.g., 1,000 mi^2) was used, the effect of terrain at a transposed location would be related directly to the shape and orientation of the 1,000-mi^2 area selected. This factor, therefore, indicated use of the 10-mi^2 area as most appropriate.

The 24-hr duration was selected because of the reliability of data for this duration. For storms before 1940, the amount of recording raingage information is relatively sparse. Determination of amounts for durations less than 24 hr for these storms is based on only limited data. This indicates use of a storm duration of 24 hr or longer. A review of the important storms in this region shows several that did not last the entire 72-hr time period of interest in the present study. Most notable of these are the Gibson Dam, MT storm (75) and the Cherry Creek (47), Hale (101), CO storms. These two factors made selection of the 24-hr duration most appropriate. Selection of this duration also had the advantage of minimizing the extrapolation required to develop PMP estimates for the range of durations required in the study.

DOCUMENTATION AND INDEX SELECTION

STORM ID/DATE, REMARKS: Gibson Dam, MT (75) 6/6-8/64

EVALUATION SCALE: COL.D 0-9; COL.E 1-9 MODULES 1-3: COL.F: IS THE SUM OF COLS. D&E. COL.D: HOW ADEQUATE IS THE INPUT INFORMATION FOR THE REQUIREMENTS SET BY MODULE'S TECHNIQUE. COL.E: HOW LIKELY IT IS THAT THIS TECHNIQUE WILL ESTIMATE THE CORRECT INDEX VALUE BASED ON ITS ASSUMPTIONS? FOR MODULE 4 SEE SELECTION RULE. OVERALL RULE: SELECT INDEX VALUE WITH LARGEST COL. F SCORE. LARGEST SUBSCRIPT BREAKS TIES.

MODULE	PARAMETER	VALUE (A)	B	C	REMARKS	D	E	F
Ø	CATEGORY	10mi²/24 hr						
	RCAT	14.9						
	BFAC	14.2						
	MXVATS	16.4						
	DADRF	.91						
	PA	.40						
	PC	0						
1	RNOVAL	7.5						
	PCT1	.43						
	I_1	6.4				7	7	14
2	AI	1.0						
	LOFACA	6.0						
	PB	.1						
	LOFAC	5.7						
	HIFX	6.0						
	DADFX	5.5						
	PA^{-1}	2.5				7	6	13
	PX	13.7						
	n	1						
	$\sum(F_1+B_1)$	.8 + .4 = 1.2						
	PCT2	.57						
	I_2	10.7						
	PCT22	.72						
3	COLUMN	A	B	C	ma = moist adiabatic saturated			
	INFLOW DIR.	080						
	INFLOW SPD.	23ms⁻¹			na = not applicable			
	GRAD. ELEV.	.045	.8	1				
	W_o	1.0			Grad. Elev measured upwind of isohyetal max between 6000 and 7000 ft			
	STABILITY	ma	.6	1				
	A_o	.7				8	7	15
	SURFACE		.7	1				
	UPPER AIR		.85	2				
	RAOB		.6	1				
	SATELLITE		na					
	RADAR		na					
	P_a	.75						
	PCT3	.49						
	I_3	7.3						
4	(PCT22 + PCT3)/2	.61						
	I_5	9.1						15
	(PCT1 + PCT3)/2	.46						
	I_4	6.9			RETURN TO MAIN FLOWCHART			15

Figure 7.9.—Completed module 5 documentation form for Gibson Dam, MT storm (75) of June 6-8, 1964.

APPENDIX 4

EXTREME LOCAL STORMS

Chapter 11 of this report discusses development of local storm PMP for the Pacific Northwest based on a survey of significant storm events. In the course of that effort, additional information was compiled that may be of interest or provide clarification to some of the results obtained in the study. While this additional information was considered in the report's development, the detailed discussion was believed unnecessary to the chapter and has been relegated to this appendix. The interested reader may wish to refer to Chapter 11 while considering the information contained in this appendix.

Extreme Local Storm Discussions

A brief discussion of some of the more important PMP controlling storms is presented in this section. Some of the distinctive characteristics and significant aspects regarding these storms are given.

Aberdeen 20 NNE, Washington - May 28, 1982

The extreme local storm at Aberdeen 20 NNE, Washington, occurred under comparatively rare synoptic conditions for the development of extreme local storms in the Pacific Northwest.

Aberdeen 20 NNE, Washington, is located some 25 miles inland from the Pacific Ocean at an elevation of 435 feet in the foothills of the Olympic Mountains to the northeast. West and southwest of the station to the Pacific is essentially free of barriers, so that the moisture source for storms is almost exclusively from this body of water. During the storm of May 28, 1982, 2.4 inches fell in a sixty-minute period ending at 1530 LST, with 2.3 inches in 45 minutes, 1.8 inches in 30 and 1.1 inches in the most intense 15-minute period. The occurrence of the storm in May was also somewhat untypical of extreme Pacific Northwest storms, although this pattern may not hold true along the coast.

Many of the synoptic features present in other extreme local storms in the Pacific Northwest were absent prior to the Aberdeen storm. The position of the storm event relative to the 500-mb trough (or closed low, in this case) was to the west of it both before and after, with upper-level winds from the north-northwest. This was a very infrequent occurrence among the extreme storms; in fact no other storm had due north winds at 500 mb, although several had west-northwest winds. An unseasonably deep low (546 dm versus seasonal mean height of 564 dm) at 500 mb, moved into Washington on the 27th. Scattered light rainfall associated with this system fell statewide on the 26th and 27th, although no heavy rains were reported. On the 28th the low drifted slowly southeastward, filling slightly. Close inspection of the 500-mb map also reveals a jet maxima of 45 kt. near Vancouver Island, which appeared to be working its way down the west side of the trough and may have been a cause of strong wind shear, an important factor in many severe thunderstorms (Browning, 1968; Doswell, 1982). Examination of the 12-hour, 500-mb height and vorticity maps from NMC reveals the existence of a very strong positive vorticity maxima (16 x 10^{-5} sec^{-1}) probably associated with this jet streak, located very nearly over Aberdeen near the time of the storm. Both these factors were likely important contributors to the rapid destabilization of the atmosphere. Very cold temperatures aloft (-25°C at 500 mb versus normal of -19°C) were also found over the area, creating sharp lapse rates and adding to the instability of the air mass.

The surface weather maps from May 28 showed a weak low (1013 mb) in central Idaho, causing rain and even some snow as far east as Montana. A weak ridge was located across the Olympic Peninsula into Vancouver Island. A strong surface high (1036 mb) was also well entrenched over the eastern Pacific Ocean near 50°N 145°W. Subsidence which is often found on the eastern side of a high pressure area may have contributed to the existence of a capping inversion over the area. Such a feature has been generally recognized as one of the important pre-severe storm indicators (Carlson, et. al., 1983). The removal of this lid to moist convection is often caused by either strong vertical motions or surface heating, both of which were present in the vicinity of Aberdeen.

Surface winds on the 0400 LST map showed a variable inflow direction to Aberdeen, indicating that low-level convergence was possible at a number of locations in the region. Although the storm took place in the mid-afternoon (beginning about 1430 LST), diurnal heating does not appear to have been a major causal factor in the development of this storm. Maximum temperatures were only in the mid 60's (°F), with partly cloudy skies prevailing much of the day. Synoptic observations from nearby stations confirm that thunderstorm activity was present across the region, although it seems to have been fairly scattered. Hoquiam FAA AP, Washington, 20 miles southwest of Aberdeen, received a thunderstorm of 36 minutes duration beginning at 1446 LST, which was reported as having moved in from the northeast. This was most likely the same storm which affected Aberdeen 20 NNE earlier. The direction of movement is consistent with the 500-mb windflow. Olympia WSO, Washington, 40 miles southeast of Aberdeen, also reported cumulonimbus to the northwest and southwest moving toward the south, but no rain fell at Olympia WSO.

In terms of moisture conditions and sources, the storm was also somewhat atypical. Although the ultimate moisture source must have been the Pacific Ocean, the northerly flow around the low brought relatively cool maritime air to the region. Surface dew points at Aberdeen and nearby stations ranged from the mid 40's to low 50's (°F) throughout the day of the storm. These values, while close to seasonal normals, were still well below the maximum values which have been observed for this area.

In summary, this was a storm characterized by the strong dynamical forcing of a vigorous upper-level low, very cold air aloft and a well-defined jet maxima with strong positive vorticity advection. At the surface, a weak flow favoring localized convergence was combined with a moderate supply of moisture and the normal diurnal heating of late May.

Girds Creek/Mitchell, Oregon - July 13, 1956

The local storm near Girds Creek/Mitchell, Oregon, on July 13, 1956, about 1700 LST, produced about 4 inches of rain in 30 minutes at the former location and 3.5 inches in the same time period (between 1600-1700 LST) at Mitchell. Located in north central Oregon at an average elevation of 4000 feet and rising southward to a plateau of 6000 feet, there is the potential for some orographic effect on storms in this area, although the influence of elevation on extreme local storms remains uncertain.

The synoptic situation prevailing up to and during this storm was one which has occurred in a significant number of extreme local storms in the Pacific Northwest. This pattern features a low or trough at the surface and a position east of an upper trough axis, usually at the 500-mb level. A deep upper low just off the California coast late on the 12th moved slowly onshore during the 13th, pulling considerable Pacific moisture inland across the northwestern states. A westward extension of the Bermuda High, centered over New Mexico, interacted with this trough to augment the northward flow of moisture across the region. The low-latitude position in mid-July of the low off California was the most climatologically unique aspect of the upper-level airflow leading up to this storm. An analysis of 700-mb moisture flow around these two features revealed a clear tongue of moisture wrapping around to the north of the closed low, with a dry slot east of the low. The axis of moist air was located in a position just to the south of the Girds Creek/Mitchell area. Surface dew points analyzed for this event showed that the 12-hour persisting dew point was 65°F, while a 3-hour persisting dew point of 67°F has been calculated. This would place the 12-hour value within 5°F of the maximum persisting dew point for that time frame.

The surface weather map features associated with this local storm were, as noted earlier, a weak low or trough and no large-scale synoptic forcing. A northward extension of the southwestern U.S. thermal low reached into Oregon and Washington on the 12th. A low (1004 mb) developed over Washington early on the 13th in response to the short wave energy moving through the base of the British Columbia upper trough. No frontal activity was evident during this period, although a trough of low pressure may have caused enough low-level convergence to act as a triggering mechanism for thunderstorm activity. The late afternoon timing of the storm indicates that solar heating again played a role in the initiation of convection in the area, with maximum temperatures reaching the low 80's.

Heppner, Oregon - May 25, 1971

The Heppner, Oregon, storm of May 25, 1971, produced rainfall totals estimated by the U.S. Army Corps of Engineers of 3.0 inches in approximately 20 minutes. The storm occurred about 1500 local time and was quite localized. The town of Heppner itself recorded only .20 inches in the quarter-hour after 1500 LST, while the very heavy precipitation fell southeast of the town.

Heppner, Oregon, which has a history of disastrous flash floods (Bauman, 1980), is located in north central Oregon along Willow Creek, some 40 miles south of the Columbia River. The town is at an elevation of about 2000 feet, while the terrain rises rapidly to the south onto a high plateau of 3000-5000 feet. Northward, the terrain slopes gently downward to the Columbia River.

The synoptic conditions associated with the Heppner storm on May 25, 1971, were similar to the Maddox Type I (Maddox et al., 1980) flash flood event. These storm are characterized by a 500-mb short wave moving up the western side of a long wave ridge. Extreme local storms in the Pacific Northwest often occur under a similar upper-level configuration. The 500-mb pattern was undergoing rapid amplification, with a digging trough off the Washington-Oregon coast and a downstream long-wave ridge building over Montana and Alberta. This trough was quite strong for late spring. Winds over the Heppner region backed from westerly to southerly during the period leading up to the storm and increased sharply from near 10 kts. to 40 kts., creating the potential for significant wind shear. The presence of such wind shear generated by jet streaks has been found to augment the intensity of the convection (Ucellini, 1990). The increasing southerly flow aloft also induced a substantial rise in low to mid-level (from the surface to 450 mb) moisture. The relative humidity over a large area including northern Oregon during the 24 hours leading up to the storm increased from about 60 percent to over 90 percent. In addition, National Meteorological Center (NMC) vertical velocity maps for this same period showed a widespread area of positive vertical motion over the Pacific Northwest, including over the Heppner area. Another ingredient for the development of strong storms was the fact that 500-mb height surface fell some 60 meters in 12 hours, from 570 to 564 dm, indicating cooling aloft and added instability. Combined with the strong upper-level diffluence ahead of the approaching Pacific trough, these elements created a very favorable situation for strong thunderstorms.

The surface weather maps during the period leading up to the Heppner storm showed the approach and passage of a weak low and associated cold front. Significant rains were reported at many other stations across the state during the day, and were also probably associated with this front. The Heppner storm occurred well after the passage of this front in the comparatively cool sector behind it. The cooling aloft however, combined with the strong late May sun, resulted in a very unstable atmosphere even behind this front. The destabilization of the atmosphere during the day is indicated by the successive development of cumulus, cumulus congestus, and finally cumulonimbus clouds at reporting stations across the region. A series of weak low pressure areas moved along the front south of Heppner during the day and provided an additional component of surface convergence, helping to focus the thunderstorm activity.

Morgan, Utah - August 16, 1958

The Morgan, Utah storm, although it occurred just outside the boundaries of the HMR-57 study area, is one of the most important storms in terms of setting the PMP for this region. It was also used in HMR 49 and HMR 55A as an extreme local storm and a detailed discussion of the meteorology can be found in HMR 50 (Hansen and Schwarz, 1981).

Opal, Wyoming - August 16, 1990

An extremely heavy local storm occurred near Opal, Wyoming, on the late afternoon of August 16, 1990. The storm produced approximately seven inches of rain in slightly less than two hours, over a very small area (Corrigan and Vogel, 1993). Although the storm took place outside the boundaries of the HMR 57 region, its proximity and location west of the Continental Divide make it an important storm nonetheless.

Opal, Wyoming, is located in southern Lincoln County in the southwest corner of the state. The coordinates are 41° 45'N, 110° 15'W, about 70 miles west of the Continental Divide. The terrain in the Opal area is generally high plateau of 6800-7000 feet above sea level, rising gently to the west. Sixty miles to the south rise the Uinta Mountains of northern Utah, while a southern extension of the Teton Range known as Commissary Ridge is located 30 to 40 miles to the northwest.

That this was truly an extreme "local" storm was evident from an examination of the 24-hour rainfall for stations within about a 60-90 mile radius of Opal. This showed that there was precipitation scattered throughout this area on the 16th, but of an extremely variable nature. Kemmerer, Wyoming, only 10 miles west of Opal, picked up only 0.10 inch on the same afternoon and Fontenelle Dam (20 miles north) received only 0.17 inch. Some more significant amounts were reported at stations in Utah and Idaho, the largest being 1.89 inches at Pine View Dam, Utah (70 miles west southwest), and 0.80 inch at Topaz, Idaho (85 miles west northwest). Hourly rainfall at nearby stations from 1400 through 1900 LST, a period encompassing the entire duration of the Opal storm, also showed little rainfall. The nearest hourly station, Mountainview, Wyoming, about 35 miles south, measured 0.10 inch ending at 1700 LST, about the time the Opal storm began. Evanston, Wyoming, 50 miles southwest had 0.20 inch over the two-hour period ending at 1500 LST. Big Piney, Wyoming, 60 miles north, had no rainfall during this period or for the day.

The meteorological conditions approximately twelve hours prior to the storm were typical of a midsummer pattern over the U.S., although certain important ingredients for heavy rainfall were undoubtedly present. The 500-mb chart for August 16 at 1200 UTC contains some important features necessary to understand the development of this storm. There is a cold core low off the northwest coast, with its associated jet maxima of about 35 kts. reaching northeastward through Oregon and Washington. More importantly however, is the short-wave trough sagging southward through Utah. The negative tilt ridge to the east, combined with this trough, are pulling extremely moist air northward into Utah and southwestern Wyoming, west of the Continental Divide. This is clearly evident from the axis of low dew point depressions extending from Ely, Nevada, northeastward to Lander, Wyoming. Opal, Wyoming, is located directly beneath this axis. It is worth noting that three other important mid-western flash flood events took place under negative tilt ridges; 1972 Rapid City, South Dakota, 1976 Big Thompson, Colorado, and 1985 Cheyenne, Wyoming (Chappel and Rogers, 1988).

The track of the 500-mb short-wave trough was clearly evident from the Nested Grid Model (NGM) height/vorticity analyses from August 16 and August 17. These depict the slow progress and intensification of the short-wave trough as it moved from southwest Utah to a position near Salt Lake City (SLC) in 24 hours (August 17 0000 UTC). The absolute vorticity increased to 12×10^{-5} sec^{-1} over a small area of northeast Utah and southwest Wyoming very close to the time of the Opal storm. Clearly, the upper-air dynamics were at a maximum in both time and space very close to Opal. The 700-mb analysis map approximately 12 hours prior to the storm (16 August 1200 UTC) showed a large pool of moisture, with 6°C dew point air through western New Mexico extending northward to about Grand Junction, Colorado (GJT). The northern edge of this moisture was marked by the -2°C dew point at Lander, Wyoming (LND), just east of the Continental Divide. Relative humidity at low and mid-levels (mean of surface to 450 mb) showed an increase from 50 percent to 70 percent during this time.

The 500-mb analysis for August 17 0000 UTC shows an upper low centered along the Utah-Wyoming border, with the short-wave trough rotating through the area. A broad pool of moisture is evident from the low dew point depression air covering all of Utah, western Wyoming, and Colorado. The precipitable water (surface to 500 mb) at SLC was 1.14 inches or 185 percent of normal and at GJT 1.08 inches or 165 percent of normal. Average relative humidity (surface to 500 mb) was also highest over northeast Utah and southwest Wyoming, with 86 percent measured at SLC. A sharp transition to lower humidity occurred east of the Continental Divide, as shown by a rapid decline in relative humidity at LND, strong confirmation of the hypothesis that the air had Pacific moisture origins.

Mid-level moisture (700 mb) was also high over most of Utah, and was moving slowly northeast with time. The 700-mb analysis for August 17 at 0000 UTC showed the highest dew point temperatures to be located over extreme southwest Wyoming, eastern Utah, and western Colorado. The thermal ridge was still centered across Wyoming, as shown by the 14°C reading at Lander, the warmest in the U.S. This is convincing evidence of the subtropical origins of the air in the region when the storm occurred. Miller (1967), in his treatise on severe storm forecasting, has stated that the 700-mb 10-14°C isotherm in summer is a favored area for significant thunderstorm outbreaks. The 700-mb wind field at this time was quite weak, with light (10 kts.) southerly winds at Grand Junction (GJT) and light and variable indicated at LND. This certainly lends support to the idea that most of the thunderstorms which developed on this day were of the single-cell variety. The importance of strong wind shear to the development of multicellular or supercell thunderstorms is well recognized; the winds in the Opal vicinity did not appear to be nearly vigorous enough for this type of storm development.

At 850 mb on August 17 0000 UTC, a pocket of 14°C dew point air was cut off over extreme northeast Utah and southwestern Wyoming. This moisture appears to have been the low-level source for the storm at Opal and the numerous other scattered storms that were reported on the 16th, mostly in northern Utah. A thermal ridge across western Wyoming was evident by the 30°C 850-mb reading at LND, while SLC is at only 16°C. Miller (1967) also points out the importance of hot air intrusion at 850 mb for the development of severe summer thunderstorms. The large temperature difference between the two stations is a result of the mid-level cloudiness over most of northern Utah, while southwest Wyoming was mostly under clear skies, adding to the potential for destabilization over Wyoming.

The surface weather map for August 16 at 1200 UTC, the morning of the storm, showed a typically disorganized summer pattern across the western U.S. The usual southwestern U.S. thermal trough extended north from Baja California, while a very weak surface low and associated trough was moving across southern Idaho, and western Utah. Weak high pressure was centered over western Oregon and the four corners area. Later in the day (2100 UTC, 1500 local) several surface developments were noted which may have contributed to the Opal deluge: 1) the eastward progression of the weak trough across Utah which assisted in scattered thunderstorm development in the state. This trough was likely an important ingredient in the surface convergence necessary for thunderstorm development at Opal as well; 2) the buildup of a large and impressively moist pool of air over northern Utah, southeast Idaho, and southwest Wyoming over the course of the day. The bulk of this moisture is concentrated over the Great Salt Lake Basin and the surrounding area and it seems reasonable to assume that some of the high dew point air in the Salt Lake vicinity reached extreme southwest Wyoming.

The most likely ingress of high surface moisture from northern Utah into southwest Wyoming appears to be through the valley of a tributary of the Bear River northeast of SLC. Isodrosotherms (for 1000 mb) drawn from hourly surface observations showed at least 70°F (21°C) dew points in southwest Wyoming. This compares with a three-hour maximum persisting dew point of 76.5°F for August, but is still at least 15°F above normal for the season, a substantial departure for the summertime.

In addition to high moisture, another essential ingredient for strong thunderstorms is adequate vertical motion, which can occur in very unstable air masses. The K index (George, 1960), best used as an indicator of summertime air mass thunderstorms, without frontal or cyclonic activity, was calculated for the surrounding radiosonde stations. Its value at 00Z August 17 ranged from 43 at Grand Junction, Colorado, to 24 at BOI. The K index was used by Lee (1973) and Hambidge (1967) in analyses of thunderstorm probability in the western U.S. Values over 40 represent nearly a 100 percent probability of thunderstorm occurrence, while above 30 gives a 80-90 percent probability of thunderstorms. It is evident that the area was well primed for the development of thunderstorms on August 16. The Showalter Index, one of the most frequently applied stability indices, fell to -2 at LND and nearly -1 at SLC, values generally associated with a high probability of severe thunderstorms. Although no severe thunderstorm watches or warnings were in effect on the afternoon of the 16th, there was some evidence that severe weather did occur. The most compelling indication was the statement from the observer at SLC at 1505 LST (2205 UTC), noting a report of a tornado touchdown five miles west of SLC. The infrequency of tornado occurrences in this region (Doswell and Keller, 1990) is an indicator of the exceptional conditions associated with this air mass.

Synoptic Study of Pacific Northwest Extreme Local Storms

In order to better understand the nature of local storms in the Pacific Northwest region, a study was undertaken to determine basic weather patterns associated with these extreme convective events. The sources for this study included the Daily Weather Map Series, hourly surface observations and supplemental meteorological data where it was readily available. These data included 3-, 6-, and 24-hourly surface maps, 500-mb height and vorticity maps, and 700-mb relative humidity and vertical velocity maps.

A total of 106 (for which adequate data and maps were available) precipitation events were selected (Table A4.1 and Figure A4.1) for study, which had at least a 50-year return period rainfall, based on data from NOAA Atlas 2 (Miller et al., 1973), and met the criteria set for local storms. A simple classification scheme was developed based on the surface and upper-air patterns which were in existence at the time the storm occurred.

Three basic surface patterns were recognized; these were 1) low pressure or trough; 2) frontal; 3) high pressure or air mass. In the mid-troposphere, usually 500-mb level, three basic upper-air patterns were also identified, resulting in a total of nine categories when the two were combined. The upper air patterns trough axis; 2) east of ridge/west of trough axis; 3) zonal.

Table A4.1.--Extreme Local Storms in the Pacific Northwest and Adjacent Areas.

LOCATION	LAT ° '	LONG ° '	ELEVATION (Feet)	DATE	RAINFALL (Inches) Max. 1-Hour	RAINFALL (Inches) Max. 6-Hour
IDAHO						
1. ANDERSON DAM 1 SW	43 20	115 29	3870	08/21/65	1.27	1.69
2. ARROWROCK DAM	43 36	115 55	3240	06/16/84	1.00	1.90
3. BENTON DAM	48 21	116 50	2640	07/29/58	0.90	0.97
4. BIG CREEK	45 06	115 20	5740	07/15/54	0.90	1.04
5. BOISE LUCKY PEAK DAM	43 33	116 04	2830	08/09/68	1.50	1.90
6. BURLEY FACTOR	42 33	113 48	4140	08/30/63	0.96	1.20
7. CLARKIA RS	47 01	116 16	2810	07/07/58	1.35	2.22
8. COEUR D'ALENE RS	47 46	116 49	2160	08/01/48	1.09	1.19
9. COTTONWOOD 2 SW	46 02	116 23	3600	08/01/48	1.50	2.10
10. COUNCIL 2 NNE	44 44	116 26	3150	07/18/76	1.60	2.80
11. GRASMERE 8 S	42 18	115 53	5200	06/08/77	1.10	1.80
12. HENRY	42 54	111 31	6350	07/21/73	1.30	1.50
13. IDAHO FALLS 6 NE	43 29	111 40	4840	07/14/54	1.13	1.13
14. IDAHO FALLS 16 SE	43 21	111 47	5710	06/15/62	0.91	1.09
15. IDAHO FALLS 43 NW WB	43 36	112 54	4780	06/13/58	1.15	1.20
16. LEADORE	44 41	113.22	6100	07/21/77	1.22	1.23
17. LEADORE	44 41	113 22	6100	08/12/63	1.14	1.19
18. MALAD	42 11	112 15	4420	07/29/69	1.00	1.22
19. MCCALL	44 54	116 07	5030	07/27/84	1.80	1.90
20. PALISADES DAM	43 21	111 13	5390	08/25/61	0.95	1.11
21. PIERCE	46 30	115 48	3190	08/15/72	1.15	1.30
22. PRAIRIE	43 30	115 35	3190	08/06/63	1.20	1.36
23. WALLACE WOODLAND PK	47 30	115 53	2950	08/12/64	1.12	1.28
24. REYNOLDS CREEK	43 15	116 45	3700	07/21/75	1.28	1.47
25. SIMON RANCH	43 15	115 45	5000	07/21/56	2.50	2.50
26. MERIDIAN	43 37	115 25	2600	06/21/67	2.75	2.75

Table A4.1.--Extreme Local Storms in the Pacific Northwest and Adjacent Areas (Cont.).

LOCATION	LAT ° '	LONG ° '	ELEVATION (Feet)	DATE	RAINFALL (Inches) Max. 1-Hour	RAINFALL (Inches) Max. 6-Hour
OREGON						
27. AUSTIN	44 35	118 30	4210	08/21/86	1.00	1.70
28. BEND	44 04	121 19	3599	08/08/50	1.24	1.58
29. BAKER 1 S	44 45	117 49	3490	06/19/69	1.03	1.16
30. BLY RS	42 24	121 03	4360	07/12/56	1.46	1.90
31. BLY RS	42 24	121 03	4360	06/07/77	1.15	1.36
32. BUNCOM 2 SE	42 09	122 59	1930	05/12/69	1.20	2.10
33. BUNCOM 2 SE	42 09	122 59	1930	06/07/83	1.45	2.66
34. BURNS WB CITY	43 35	118 57	4140	06/03/48	0.90	1.70
35. BUTTE FALLS 1 SE	42 32	122 33	2500	10/01/76	1.10	1.50
36. BUTTE FALLS 1 SE	42 32	122 33	2500	06/20/82	1.10	1.20
37. COPPER 2 NE	42 04	123 06	1780	07/20/83	1.70	1.80
38. COUGAR DAM	44 08	122 15	1260	07/10/75	1.80	2.30
39. EUGENE WB AP	44 07	123 13	360	08/21/79	1.11	1.82
40. FERN RIDGE DAM	44 07	123 18	380	06/28/84	1.50	1.60
41. GLENDALE 2 NE	44 44	123 26	1500	07/19/83	1.30	1.60
42. HILLS CREEK DAM	43 43	122 26	1280	05/31/64	0.92	1.34
43. IMNAHA	45 34	116 50	1850	08/26/66	1.15	1.32
44. IMNAHA	45 34	116 50	1850	07/27/84	1.00	1.30
45. JORDAN VALLEY	42 59	117 04	4260	08/01/65	1.20	1.20
46. JOSEPH RS	45 23	117 14	4020	07/12/75	1.10	1.20
47. LACOMB 1 WNW	44 38	122 44	610	08/16/78	1.10	1.50
48. LEE'S CAMPS	45 36	123 31	600	07/14/83	1.10	1.10
49. MARION FORKS FISH H	44 36	121 57	2450	08/05/53	1.09	1.30
50. MEDFORD WB AP	42 23	122 53	1310	05/18/56	1.40	1.67
51. MEDFORD WB AP	42 23	122 53	1310	09/05/53	1.27	1.32
52. OWYHEE DAM	43 38	117 13	2400	06/14/64	1.20	1.39
53. SALEM WB AP	44 55	123 01	200	06/10/50	1.24	1.56
54. SEXTON SUMMIT WB	42 37	123 22	3848	06/28/78	1.87	2.14
55. TILLER RS	42 56	122 57	1040	06/28/78	1.30	2.50
56. TRAIL 15 NE	42 46	122 37	2100	08/02/58	1.89	1.90
57. UKIAH	45 08	118 56	3340	07/09/75	1.90	2.10
58. UNION	45 13	117 53	2770	06/16/63	1.02	1.12
59. UPPER STEAMBOAT CK	43 29	122 36	1860	06/18/82	1.10	1.20

Table A4.1.--Extreme Local Storms in the Pacific Northwest and Adjacent Areas (Cont.).

LOCATION	LAT ° '	LONG ° '	ELEVATION (Feet)	DATE	RAINFALL (Inches) Max. 1-Hour	RAINFALL (Inches) Max. 6-Hour
60. GIRDS CREEK	44 40	120 10	4000	07/13/56	4.00	4.00
61. HEPPNER	45 20	119 33	3000	07/13/56	3.00	3.00
62. BIRCH CREEK	45 20	118 55	3000	06/22/38	2.50	2.50
63. JOHN DAY	44 25	118 53	3200	06/09/69	5.00	7.00
WASHINGTON						
64. CINEBAR 2 E	46 36	122 30	1000	06/09/53	1.20	1.99
65. CAMP GRISDALE	47 22	123 36	820	06/25/68	1.20	1.30
66. CHIEF JOSEPH DAM	48 00	119 39	820	07/25/87	0.90	1.00
67. DAYTON 2 SE	46 18	118 00	1750	07/07/78	1.20	1.20
68. DIABLO DAM	48 43	121 09	890	09/04/86	1.00	1.20
69. EASTON	47 15	121 11	2170	08/26/83	1.80	1.80
70. MAZAMA	48 37	120 27	2180	07/16/85	0.90	1.10
71. METHOW	48 08	120 00	1160	08/10/48	1.08	1.08
72. NACHES 10 NW	46 52	120 46	2380	07/07/82	1.20	1.20
73. OROVILLE 1 S	48 56	119 26	920	06/11/64	1.27	1.27
74. PULLMAN 2 NW	46 46	117 12	2545	06/16/63	1.35	1.47
75. RANDLE 1 E	46 32	121 56	950	08/28/57	1.20	1.47
76. REPUBLIC RS	48 39	118 44	2630	08/09/62	1.21	1.29
77. REPUBLIC RS	48 39	118 44	2630	07/05/58	1.00	1.10
78. SILVERTON	48 04	121 34	1480	08/05/77	1.10	1.34
79. WALLA WALLA WB CITY	46 02	118 20	950	05/26/71	0.98	1.84
80. WILSON CREEK	47 25	119 07	1280	06/18/50	1.47	1.53
81. ABERDEEN 20 NNE	47 16	123 42	440	05/28/82	2.40	2.50
82. SKYKOMISH	47 42	121 22	1030	05/25/45	1.78	1.78
83. WENATCHEE EXP STN	47 26	120 21	806	08/10/52	1.25	1.29
84. CASTLE ROCK	46 16	122 55	43	08/23/63	1.06	1.12
85. KNAPP COULEE	47 49	120 08	1500	08/15/58	1.50	1.50
86. WINTHROP 1 WSW	48 20	120 11	1755	07/29/58	3.00	3.00
CALIFORNIA						
87. ALTURAS	41 30	120 33	4460	06/06/52	1.13	1.20
88. ETNA	41 28	122 54	2910	06/07/77	1.40	1.80

Table A4.1.--Extreme Local Storms in the Pacific Northwest and Adjacent Areas (Cont.).

LOCATION	LAT ° '	LONG ° '	ELEVATION (Feet)	DATE	RAINFALL (Inches) Max. 1-Hour	RAINFALL (Inches) Max. 6-Hour
UTAH						
89. FARMINGTON WHSE STA	40 58	111 53	4330	06/01/63	1.75	2.24
90. LOGAN USAC	41 45	111 48	4780	08/11/83	1.10	1.30
91. OGDEN PIONEER PH	41 15	111 57	4350	08/18/79	1.30	1.40
92. OGDEN SUGAR FACTORY	41 14	112 02	4280	09/08/67	1.20	1.20
93. OGDEN WBO	41 12	111 58	4440	06/18/49	1.04	1.26
94. MORGAN	41 03	111 38	5150	08/16/58	6.75	6.75
95. NORTH OGDEN	41 20	111 55	4800	09/07/91	1.75	5.50
NEVADA						
96. CONTACT	41 47	114 45	5370	06/13/83	1.00	1.20
97. ELKO	40 50	115 47	5080	08/27/70	3.47	4.13
MONTANA						
98. AUGUSTA	47 29	112 23	4070	07/05/51	1.80	1.83
99. CAMERON	45 12	111 41	5500	07/01/65	1.55	2.26
100. CUT BANK CAA AP	48 23	112 22	3840	07/11/56	1.30	1.37
101. DUTTON 6 ESE	47 51	111 35	3590	07/02/66	2.15	2.89
102. KALISPELL WB AP	48 18	114 16	2970	06/29/82	2.57	2.68
103. LIVINGSTON FAA AP	45 42	110 27	4690	08/24/79	2.63	3.19
104. STEVENSVILLE	46 31	114 06	3370	07/31/83	1.70	1.90
105. WISDOM	45 37	113 27	6060	06/17/50	1.20	1.36
WYOMING						
106. OPAL	41 45	110 15	6900	08/16/90	5.75	7.00

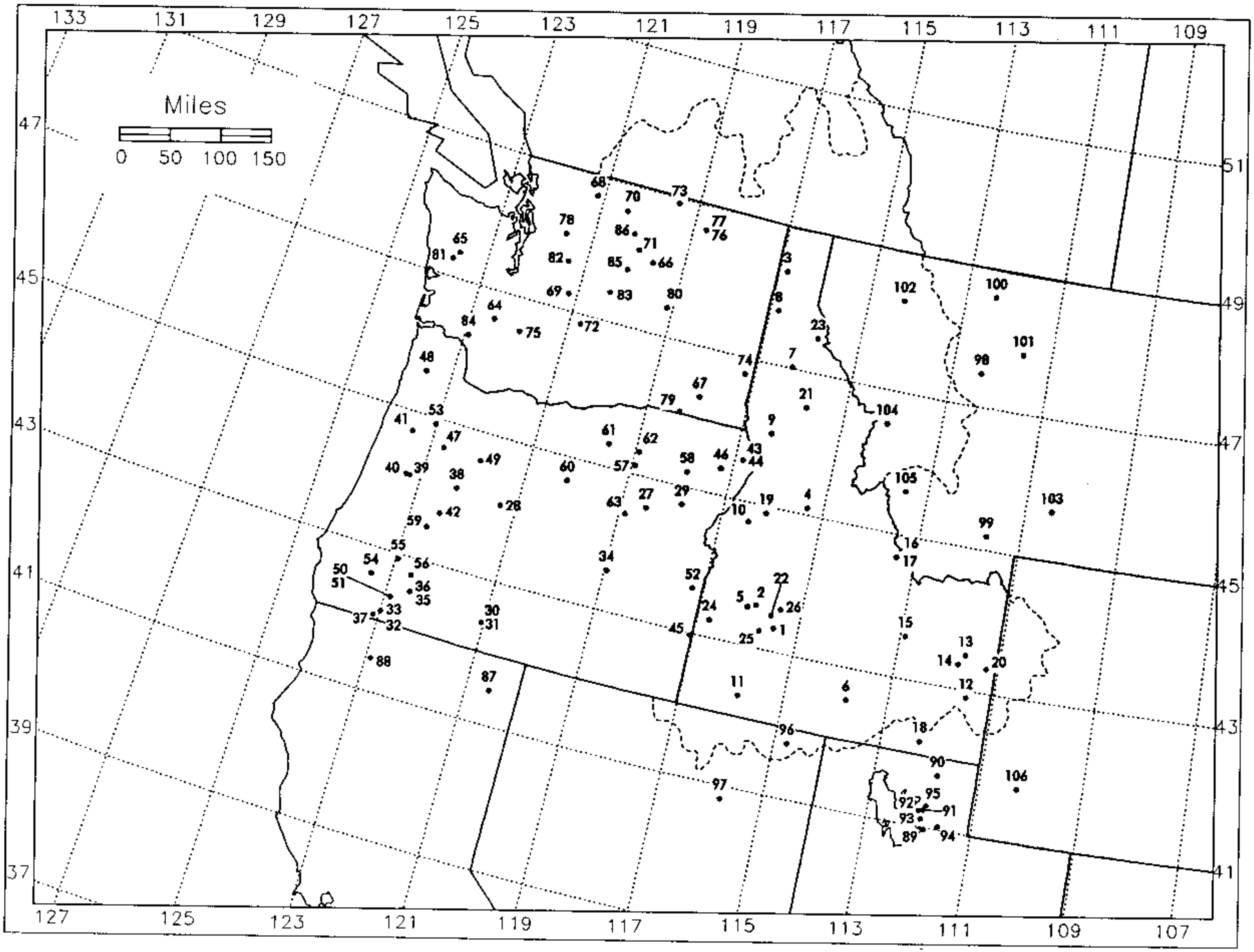


Figure A4.1.--Location of extreme local storms.

Table A4.2 shows the frequency of occurrence of the nine categories selected and Table A4.3 shows the mean values for selected meteorological variables within each group. For comparison, Table A4.4 shows mean height and temperature at 500 mb for three selected stations in the region.

Table A4.2.--Frequency of synoptic categories

Synoptic Pattern: SFC/UA	1. W of Ridge/ E of Trough	2. E of Ridge/ W of Trough	3. Zonal	Total
1. Low; trough	45	2	4	51
2. Frontal	19	3	5	27
3. Air Mass; High	19	3	3	25
Total	83	8	12	103

Source: Extreme local storm database

Table A4.3.--Synoptic types - mean values.

Type/ Means (#)	1-hour Prec. (in.)	500-mb ht. (feet)	500-mb temp. (C)	500-mb wind speed & dir. (kts. and deg.)	Max. sfc. temp (F)	24-hour per. dew point (F)	Maximum dew point (F)
11 (45)	1.67	18835	-14.1	23.7 215	84.3	55.6	60.1
12 (2)	1.05	19000	-13.0	13.5 230	94.0	58.0	62.5
13 (4)	1.27	18950	-13.7	22.0 275	88.3	57.0	60.8
21 (19)	1.23	19000	-12.0	21.4 228	84.2	56.6	62.0
22 (3)	1.17	18767	-14.3	18.3 280	84.7	51.7	65.0
23 (5)	1.39	18940	-12.0	23.0 268	78.8	51.0	57.8
31 (19)	1.75	19213	-9.7	21.5 234	87.6	57.9	62.6
32 (3)	1.76	18450	-21.0	26.0 330	66.0	47.7	51.7
33 (3)	1.85	18833	-14.7	19.3 277	76.3	54.7	56.0

Table A4.4.--Average monthly values of 500-mb. temperature (°C) and geopotential heights (feet) for three regional stations.

Station	May	June	July	August	September	October
Boise, ID	-18.31 18580	-14.10 18841	-10.45 19150	-11.25 19101	-12.81 18950	-15.43 18783
Medford, OR	-18.46 18572	-13.99 18829	-10.33 19110	-11.20 19065	-11.66 18986	-14.45 18799
Spokane, WA	-21.06 18346	-17.54 18563	-15.15 18829	-14.41 18802	-14.52 18750	-18.54 18458

Source: Crutcher, H. L. and J. M. Meserve, "Selected Level Heights, Temperatures and Dew Points for the Northern Hemisphere" Naval Weather Service Command, Washington, D.C., 1970

Persisting Dew Point Data

In order to develop maps of persisting 3-hour dew points, data for the period from 1948-1974 were extracted from hourly data tapes for 27 stations in or near the study region (Figure A4.2). From this data base, periods of elevated dew points were selected for analysis.

These high dew point episodes were examined meteorologically to insure that only those that occurred under conditions favorable for the development of local storms were included. High dew points resulting from highly stable, inversion conditions, or when rain was occurring at the point of observation were not considered for further analysis for several reasons. First, an air mass that is too stable is very unlikely to be associated with the strong upward vertical velocity needed to produce heavy rain. Second, extremely high moisture in an inversion situation may become trapped in the lowest layers of the atmosphere, leading to an overestimate of the vertical moisture distribution and inaccurate in-place adjustments. Third, hourly precipitation data were checked for the occurrence of scattered short-duration afternoon and evening rainfalls, typically the result of local storm rainfalls. Rain at the time of the observation could give an unrealistically high value for that station. Hourly observations for individual weather stations were also examined to check for potential observational error in the dew point measurements and to obtain more detailed information about the synoptic situation.

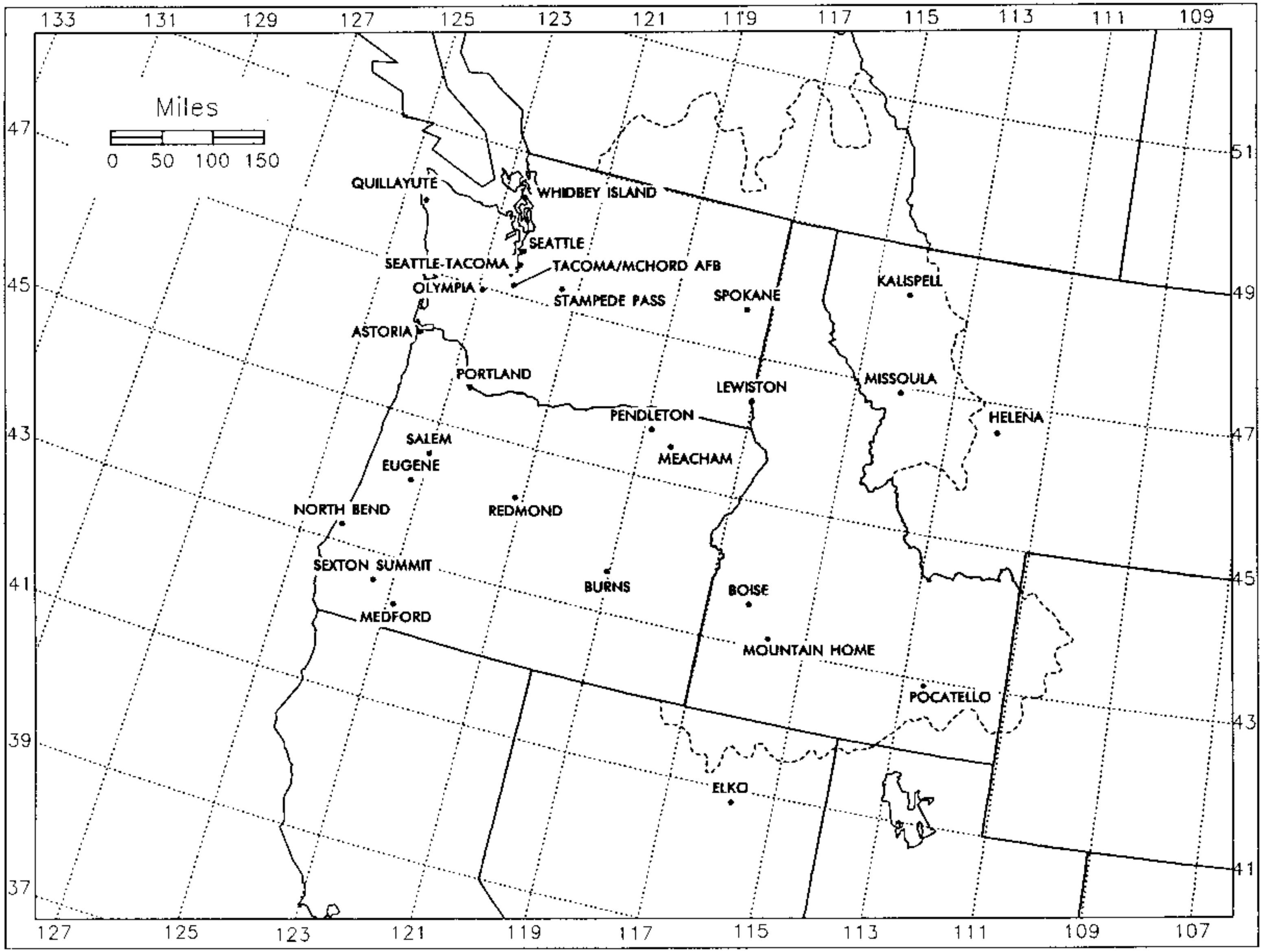


Figure A4.2.--Observing stations providing data for 3-hr maximum persisting local storm dew point analysis.

Subregional Classification

A subregional classification scheme was developed to help overcome the relative paucity of high dew point episodes on days also favorable for local storms. This enhanced the utility of the dew point analysis by grouping the available data within similar climatic zones. Figure A4.3 shows the subregional boundaries, which are based on:

1) climatological variations (discussed below),
2) significant topographical barriers

In order to develop and compare the climatic characteristics of the individual subregions, the ranges of important climatic variables were tabulated and can be found in Table A4.5. This table includes the annual range of daily temperature maxima, the mean annual daily temperature range, the annual range of 12-hour maximum persisting general storm dew point, the mean annual number of thunderstorm days, the average percentage of the annual thunderstorms occurring from May through September, and the average annual precipitation. Data for Table A4.5 was obtained from Local Climatological Data for individual stations (National Climatic Data Center, 1984), the Climatic Atlas of the U.S. (U.S. DOC, 1968) and from the climatological studies of Trewartha and Horn (1980), Haurwitz and Austin (1944), Easterling and Robinson (1985), Changnon, (1988, a and b) and Gabriel and Changnon (1989).

A discussion of the subregional climatic characteristics, including the data list in Table A4.5, follows:

Subregion 1, which is restricted to the lowland coastal strip inland to the crest of the coast ranges, has a moist, maritime climate with 40-240 inches of mean annual precipitation (MAP), dominated by unmodified Pacific Ocean air masses which move generally unobstructed across the subregion. The thermal influence of the Pacific air is illustrated by the narrow temperature range (about 15°F daily [ΔTdly] and 20-25°F for annual highs [ΔmaxT]), and the low annual variation of 12-hour maximum persisting dew point [ΔmTd] (less than 10°F).

As noted by Trewartha and Horn (1980), summertime in this area is dominated by the eastern limb of the Pacific anticyclone with its attendant subsidence and the very low (3-10) average number of thunderstorm days per year [TSTM]. Much of the activity that does occur is associated with cold season general storms, as only 25 percent of the annual thundershowers occur from May through September [%TMS = 25]. At Astoria, Oregon, for example, of the 9 thunderstorm days per year, only two occur in July and August (one each month). Only two of the 106 heavy precipitation events in the extreme storm database occurred in subregion 1.

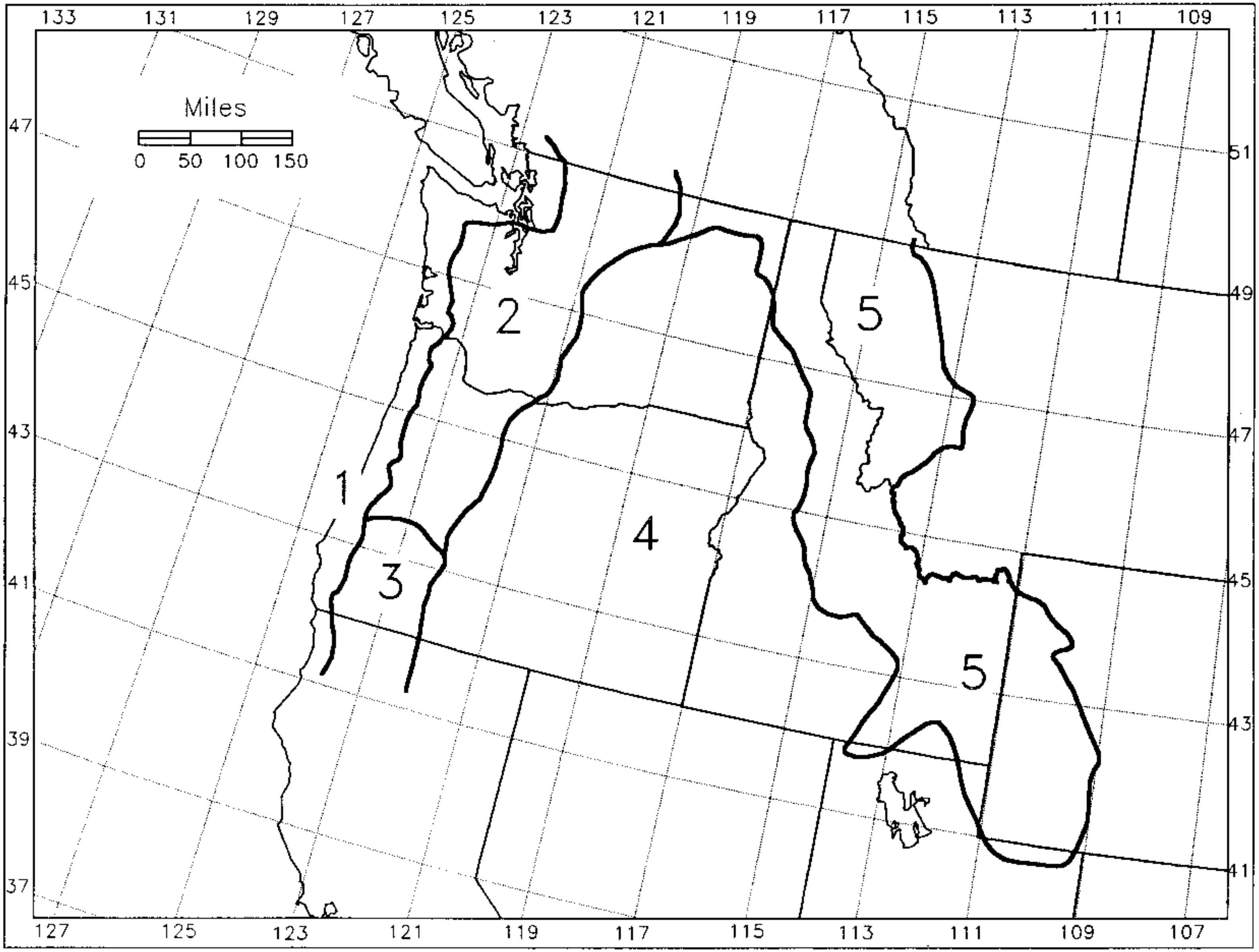


Figure A4.3.--Subregions for local storm analysis

Subregion 2 encompasses the area from the coast range crests inland across the Willamette Valley and Puget Sound to the Cascade crestline. This region also has a moist climate (35-180 MAP) which is dominated by air of Pacific origin. Modification of these air masses does take place however, as precipitation is wrung out on the windward side of the coast mountains. This explains the very wide range in MAP, with a pronounced "rain shadow" effect to the east. Conversely, orographic precipitation is enhanced along the windward slopes of the higher Cascade Range. The stabilizing effect of the Pacific is sufficient to keep thunderstorm occurrences [TSTM] at less than 10 per year, but there is a marked shift in their seasonal frequency, with 70 percent occurring during the warm season. The maritime influence is still reflected by the low annual variation of maximum persisting dew point [ΔmTD] but the change in annual temperature maxima [ΔmaxT] are considerably greater than in subregion 1, at 30-40°F.

Table A4.5.--Subregional climatic characteristics.

Sub-Region	ΔmaxT(°)	ΔTdly(°)	ΔmTd(°)	TSTM	%TMS	MAP (in.)
1	20-25	14-16	8-9	3-10	25	40-240
2	30-40	10-22	5-8	5-8	70	35-180
3	40	15-27	5-10	5-10	85	15-50
4	50	18-27	10-15	10-15	85	10-20
5	55	23-35	20-35	20-35	95	10-50

ΔmaxT
Difference between average January and July daily high temperatures

ΔTdly
Difference between mean annual daily high and low temperatures

ΔmTd
Difference between annual highest and lowest values of 12-hour maximum persisting general storm dew point

TSTM
Mean annual thunderstorm days

%TMS
Average percentage of annual thunderstorms occurring from May through September

MAP Mean annual precipitation

Subregion 3, comprises a relatively small area stretching from the southern edge of the Willamette Valley into the higher coastal ranges of Oregon and northern California. The chief differences between this area and subregion 2 are the rougher topography and the influence of lower latitude on the development of heavy storms. The climate is similar to subregion 2, but there is less rainfall in most areas (MAP of 15-50 inches) and a slightly greater temperature range. The most important distinction however, seems to be the greater importance of summer thunderstorm activity (85 percent versus 70 percent). The reasons for this increase in convective storm frequency are most likely related to the rugged terrain which serves to enhance differential solar heating, increases low level convergence and imparts additional upward motion on air parcels. The stabilizing influence of the Pacific Ocean is also significantly reduced in this rough terrain.

Subregion 4 extends from the Cascade Range crests eastward across the broad interior of Washington, Oregon, and southeast Idaho, into the foothills of the Rockies. This expansive area has a dry to nearly arid climate of low annual rainfall (10-20 inches) and extremes in temperature [ΔmaxT], typically about 50°F. Despite the low annual rainfall amounts, thunderstorm activity [TSTM] is more frequent than in subregions 1, 2, and 3, at about 10-15 thunderstorms per year for any particular station. Eighty-five percent of these occur from May through September [%TMS]. It is notable that 10 of the 15 extreme local storms listed in Table A4.1 occurred in this subregion. This region is effectively shielded from the Pacific by the coastal and Cascade barriers, reducing moisture inflow from the west. The southern portion of this area is periodically affected by Gulf of California or possibly Gulf of Mexico moisture when there is a northward extension of the southwest monsoon pattern.

Subregion 5 covers the area from the foothills of the Rockies to the Continental Divide where the study area terminates. This is also an interior climate, but most of the area is mountainous, so there is a great deal of variability within the subregion itself. The annual temperature range [ΔmaxT] is even greater than that of subregion 4, averaging about 55°F. There is also significant moisture variability, with a ΔmTd range of 20-35°F across this area.

The southern portions of this region may also be affected by the southwest monsoon pattern. Summer thunderstorm activity is at a maximum for the entire northwest in this subregion, with 20-35 thunderstorms per year [TSTM], 95 percent of them occurring in the warm season [%TMS]. Similar to subregion 3, it appears that terrain has a marked impact on the development of local storm activity in this area. An examination of the extreme storm database showed that three thunderstorms with hourly precipitation exceeding 2 inches occurred in this subregion, out of a total of 10 for the entire study area.

Analysis

The initial step in preparation of persisting 3-hour dew point maps, was to group extreme dew point cases within their respective subregions. Initial dew-point patterns were then drafted within each subregion, relying on 12-hour persisting dew-point patterns from previous studies for general guidance. The monthly maps were subsequently analyzed for the study region as a whole, smoothing subregional transition areas and shaping the overall patterns to account for the major moisture sources, significant topographic barriers, and seasonal air temperature and pressure patterns.

Seasonal and regional consistency checks were performed to eliminate any anomalous or spurious data and to ensure that a relatively smooth dew-point pattern emerged. The difference field between the 3-hour maximum persisting local storm dew points and the 12-hour maximum persisting general storm dew points was also prepared. The 3-hour local storm dew points were found to exceed the 12-hour general storm dew points by 2-7°F, which is consistent with McKay's (1963) analysis as described earlier.

In-Place Maximization

The in-place adjustment for maximum moisture for local convective storms is the ratio of the precipitable water for the maximum persisting 3-hour (reduced to 1000 mb) dew point at a particular location to that for the representative persisting 3-hour (1000 mb) dew point for the individual storm site. The local storm moisture adjustment procedure differs from the general storm procedure because of the often highly localized character of local storms and the relatively disorganized nature of their moisture inflow. The primary procedural difference is that representative dew points for local storms are taken as near as possible to the storm in any direction from the storm location, because it is assumed that local storms can occur independently of any sustained moisture inflow (Hansen et al., 1988). This is different from the procedure for general storms in which a distinct inflow direction is specified. The maximum persisting dew point is read at the storm location for the time of year in which it occurred.

Secondly, the in-place adjustment for any local storm is restricted to a maximum of 1.50, the same upper limit adopted by Hansen et al. (1988). This is because the synoptic and mesoscale conditions of major local storms do not appear to be capable of accommodating more moisture than this. In addition, the network of stations providing dew-point observations may be too sparse to fully represent the moisture field in the vicinity of such highly localized storms. It is possible under such conditions that more moisture could be present at the storm site than at the location of the storm dew-point measurement. This would result in an underestimated actual storm dew point and an unrealistically high moisture maximization.

Adjustment for Elevation

Background

Both HMR 43 and HMR 49 studies used 5,000 feet as a maximum elevation, above which a steady, systematic decrease was assumed for local storm PMP. For the region between the Continental Divide and 103°W, no variation was expected within 1000 feet of 5000 feet, with a decrease above that level based on a percentage of the decrease in precipitable water with altitude (Hansen et al., 1988). In the study for the southwest, 6-hour recorder rainfall maxima versus elevation for stations in Nevada, Utah, and Arizona showed a decrease in the among-station maximum precipitation above 4000 to 5,000 feet, although a possible reason for the decrease was a smaller data sample at the higher elevations.

Due to the decrease in atmospheric moisture and temperature with height, a reduction in the local storm precipitation with elevation can be expected at some point. How this decrease in moisture might be offset by increased local storm efficiency due to high terrain is not clear. Factors contributing to intensified convection at higher elevations include increased vertical velocities, strong differential heating of slopes, and enhanced convergence.

One study examining the influence of elevation on the intensity of rainfall in the Pacific Northwest was that of Cooper (1967). Using data from 93 rain gages in the Reynolds Creek watershed in southwest Idaho, he determined that there was no discernible relationship between elevation and peak intensity or total amount of rainfall at elevations from 3600 to 7200 feet.

Several researchers have noted the tendency for there to be enhanced convection over mountainous terrain. Abbs and Pielke (1986) found that areas of upslope flow and increased convergence of moist, unstable air become preferred regions for convective development. Such areas tended to maximize in the high terrain near the Continental Divide in Colorado. Toth and Johnson (1985) found that elevated locations were zones of convergence maxima in Colorado and correlate well with areas favored for deep convective development. An earlier study by Henz (1974) also documented the tendency for preferred thunderstorm formation zones to exist over elevated areas in the Colorado Front Range.

Heavy thunderstorm rainfall (intensities of 2 inches per hour or greater) at 7500 feet or higher in the Colorado Front Range from 1965-1988 were studied by Henz and Kelly (1989). Using information from the NOAA publication Storm Data, they found 24 cases of thunderstorm rainfall of 2 inches or greater from April to September during the period from 1979 through 1988. All were short duration events, usually less than two hours and 83 percent occurred at least partially above 8000 feet. Among the factors cited as contributing to heavy rains at high altitude was a tendency for the storms to remain stationary or move very slowly over their formation zones.

Recent studies by Jarrett (1990) and Jarrett and Costa (1989) have utilized paleohydrologic techniques to estimate the frequency of high elevation flood-producing storms in Colorado. These works tend to discount the existence of very heavy rainfall above 8000 feet, while contending that such storms are not infrequent below 7500 feet, implying a very rapid decrease above a certain critical elevation threshold. Clearly, further study will be needed to verify the validity of these findings.

Analysis

In an effort to understand how thunderstorm rainfall diminishes with elevation in the Pacific Northwest, an investigation was conducted using the data base of heavy local storms in Table A4.1. There was no clear evidence of an elevation-dependent change in local storm precipitation to about 5,000-6,000 feet. While the maximum observed local storm precipitation does decrease somewhat above 5,000 feet, such a decrease could also be explained by a relative lack of station coverage. For example: in 1975, (the chronological mid-point of available recorder data), out of 256 recorder stations with at least 10 years of data in the study region, only 25 were at an elevation of 5,000 feet or greater, and merely 4 were at an elevation of 6,000 feet or greater. Furthermore, there are relatively little bucket survey data above 5,000 feet because of low population density.

A statistical regression analysis using the local storms found in Table A4.1 showed no significant variation throughout an elevation range of 43 to 6,350 feet above sea level. A plot of these data is shown in Figure A4.4. This supports a possibility of maximum local storm precipitation to at least 6,000 feet, but it is important to note that only 4 of the 105 thunderstorms in the data set occurred at or above 6,000 feet. While this indicates that the data set at high elevations is too sparse to provide very reliable statistical information, it is also true that the percentage of 50-year return-period storms at or above 6000 feet (4/105 = 3.8 percent) is greater than the percentage of 1965-75 recorder stations at or above 6,000 feet (4/256 = 1.6 percent) by a factor of 2.4. This tends to support a greater likelihood of heavy local storms above 6,000 feet than at lower elevations.

It is also important to note that the storm which produced the greatest hourly precipitation in or near the study area (Morgan, Utah, August 16, 1958: 6.75 inches in 1 hour) occurred at an elevation of 5,150 feet, which also provides justification for taking maximum local storm precipitation potential to elevations exceeding 5,000 feet. In addition, the extreme local storm at Opal, Wyoming, on August 16, 1990 (7.0 inches in 2 hours), occurred at an elevation of about 6,900 feet. The forgoing analysis suggests that 6,000 feet may be a more accurate approximation of the elevation above which local storm precipitation will begin to decrease, at least in this region of the country. This conclusion, based on a much expanded data base from within and around the study region, reflects the lack of clear evidence of any elevation-dependent decrease of maximum local storm precipitation potential in the 5,000-6,000 foot range.

For elevations above 6,000 feet, a decrease in local storm PMP of 9 percent per thousand feet above 6,000 feet was utilized, approximating a pseudo-adiabatic decrease in the moisture available for convective activity. Figure 15.37 (Chapter 15) compares the moisture variation based on this approximation to the change of column moisture, with elevation in a saturated pseudo-adiabatic atmosphere for 1000-mb dew points of 60, 70 and 80 degrees (F). The adopted elevation adjustment was also based on the assumption that the surface dew point would be representative of total column moisture and that the effectiveness of local storm mechanisms would not change appreciably with height above 6,000 feet. This procedure for elevation adjustment of local storm PMP above 6000 feet is consistent with the procedure adopted in the PMP study of the region between the Continental Divide and 103°W (Hansen et. al., 1988), in which an explicit saturated pseudo-adiabatic moisture adjustment was adopted above 5,000 feet.

Indirect empirical support for the validity of this approach may be found in the study by Henz and Kelly (1989). He reported rainfall amounts as great as 1.9 inches in 10-15 minutes at 8,500 feet and 2.25 inches in 25 minutes at 9,000 feet. These amounts were less than PMP would be at their respective areas of occurrence, using the elevation adjustment procedure just described in Hansen et. al. (1988), about 5.5 and 6 inches, respectively. With no other data supporting the idea of even heavier rains at very high elevations, it was assumed that this adjustment would yield an adequate reduced estimate of PMP in higher terrain.

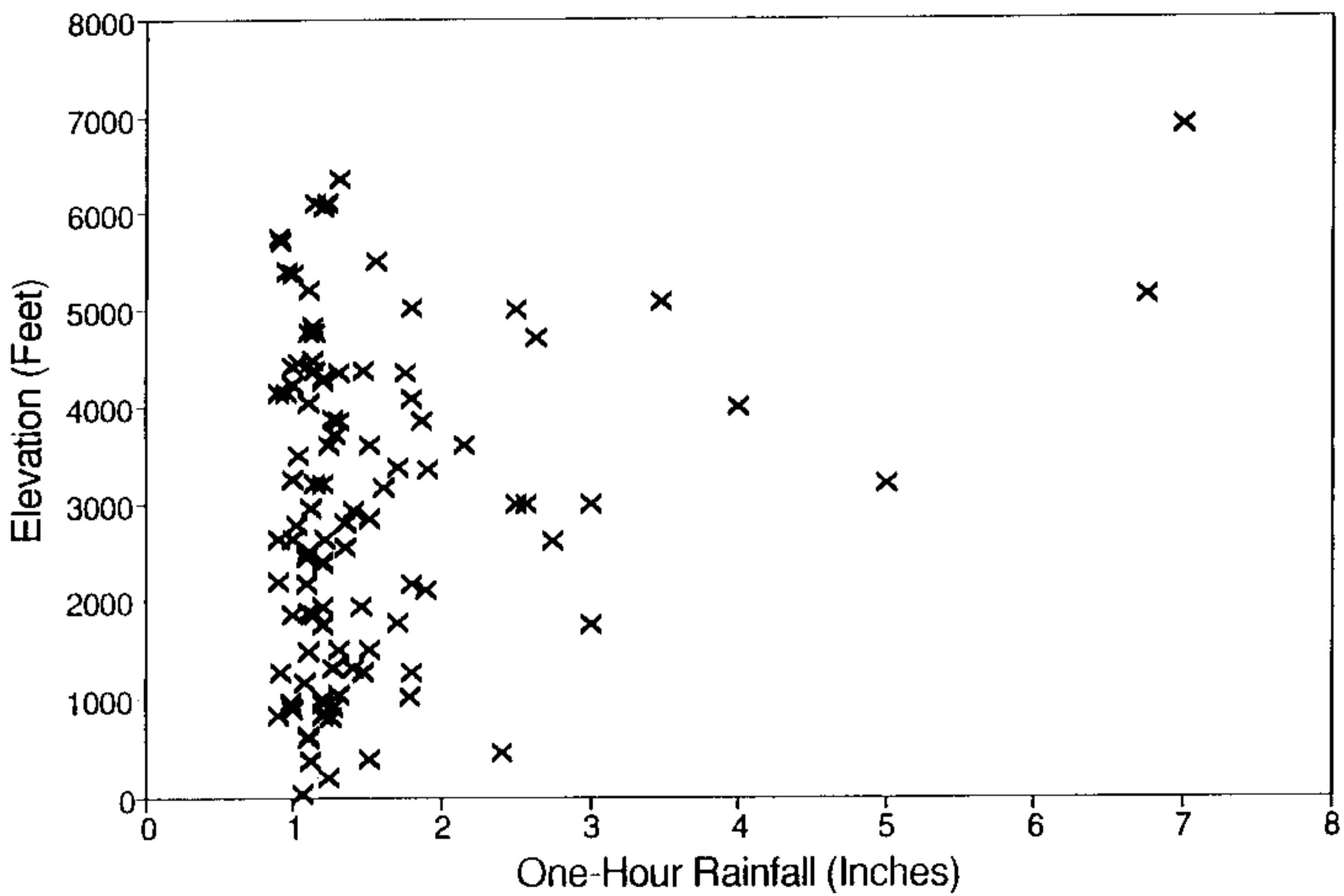


Figure A4.4.--One-hour rainfall versus elevation for storms in Table A4.1

HORIZONTAL TRANSPOSITION

Background

As in the general storm analysis, transposition is defined as the process of transferring observed precipitation rainfalls from their location of occurrence to another location where a storm with essentially the same rainfall mechanism is thought to be possible. In transposition, the rainfall is adjusted to account for the difference in moisture availability, based on the persisting dew point maps, between the original storm site and the transposed location.

Analysis

The transposition procedure for Pacific Northwest local storms is the same as that for general storms, with the following exceptions:

1) the elevation adjustment follows the procedure outlined in this Appendix (no adjustment below 6,000 feet), and

2) no adjustment for barrier elevation is made for local storms because local storms often result from highly localized accumulations of moisture rather than large-scale inflow.

3) the climatic subregions were adopted as general guidelines for transposition, but not as strict boundaries.

The key concept here was that the climatic zones limits should not constitute rigid barriers in the atmosphere, but would represent transitional regimes. For instance, it was not considered acceptable that a storm in zone 4 could be transposed into zone 1, whereas transposition from zone 4 storm into portions of zone 2 was allowed, using terrain for additional guidance.

As in the general storm procedure, no elevation adjustment is made for the first 1,000-feet or lower elevation increase when a storm is transposed to a higher elevation. This procedure for local storm transposition is consistent with the most recent major PMP study covering the adjacent area from the Continental Divide to 103° W area (Hansen et. al., 1988).

APPENDIX 5

This appendix provides some background information and an example of the procedure for using the snowmelt and wind criteria for a basin. The background and procedure is extracted directly from Chapter VIII of HMR 43, with the exception that the figure numbers have been changed to refer to those in Chapter 15 of this report (Computational Procedure).

Introduction

Evaluation of runoff involves the contribution of snowmelt. Snowmelt computations require generalized temperature and wind sequences during the 3-day PMP storm and for 3 days prior.

Temperatures and Dew Points During the PMP Storm

Temperatures during the PMP storm are equal to maximum dew points, using the simplifying assumption of a saturated adiabatic atmosphere. Maximum storm dew points were determined in Chapter 4.

Temperature and Dew Points Prior to PMP Storm

For combined rain and snowmelt flood determinations, a sequence of high temperatures for several days prior to rain storms is generally the most critical situation. With this in mind, highest temperatures observed prior to major storms in the Northwest were determined. An envelope of the difference between these prior temperatures and the temperatures during the storms was then assumed applicable to PMP temperatures at the beginning of the PMP storm.

Sources of storms surveyed included preliminary Corps of Engineers storm data, the controlling storms listed in the Cooperative Studies Snake River Report Number 11 (U.S.W.B., 1953) and Weather Bureau Technical Paper Number 38 (U.S.W.B., 1960), as well as storms giving record 24-hour rainfall amounts. Daily mean temperatures and precipitation amounts were obtained from a mountain station near the 24-hour heavy rain center and from a nearby upwind first-order valley station. For a particular season and region, the critical temperature differences were approximately the same at the two stations.

Temperature differences for establishing the critical upper envelope plotted by dates of occurrence showed significant seasonal trends. These trends and the range of temperature differences depended on whether the storm was east or west of the Cascade Divide. Durational curves of the temperature differences throughout three days were therefore drawn for each region. These curves are shown in Figure 15.13. As this Figure shows, cool-season antecedent temperatures are at least as low as those observed during the storm. In late spring and early autumn, antecedent temperatures are higher than during the storm.

Example of Snowmelt Winds and Temperatures for a Basin

As an example, snowmelt data for mid-May for the Blackfoot River drainage above Blackfoot Reservoir, Idaho, will be determined.

Basin average elevation: 7000 feet

Lettered and numbered steps in this example are identical to those in the outlined procedure discussed in Chapter 15 (pages 206-208).

A. Temperature and Dew points During PMP Storm

(1) Average 12-hour mid-May maximum dew point over basin (Figure 15-22): 63.0 °F.

(2) Precipitable water (W_p) for 63.0 °F (Figure 15.30): 1.59 inches.

	6-hour period											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
(3) Ratios of W_p each 6-hour period to maximum 12-hour W_p (Figure 15.31)	1.04	1.00	0.97	0.95	0.92	0.90	0.89	0.87	0.85	0.84	0.82	0.81
(4) = (2) x (3) W_p (ins.)	1.65	1.59	1.54	1.51	1.46	1.43	1.42	1.38	1.35	1.34	1.30	1.29
(5) Mid-May 1000-mb. temperatures (°F) each period (Figure 15.30):	63.6	63.0	62.4	61.9	61.4	61.0	60.6	60.2	59.8	59.4	59.0	58.7
(6) Mid-May temperatures (°F) reduced to 7000 feet (Figure 15.32):	45.4	44.7	44.0	43.2	42.5	41.9	41.3	40.8	40.3	39.9	39.4	39.0
(7) Rearrangement of temperatures to conform to sequence of PMP increments (sequence (a) of Figure 15.12 used in this example): °F	40.3	41.3	42.5	44.0	45.4	44.7	43.2	41.9	40.8	39.8	39.4	39.0

B. Temperatures Prior to PMP Storm

(1) Temperature for first 6-hour period of PMP storm from A(7): 40°F

	Hours Prior to Storm											
	6	12	18	24	30	36	42	48	54	60	66	72
(2) Mid-May differences between temperatures at indicated times prior to first 6-hour period of storm (Figure 15.13):	4	7	11	15	15	15	15	15	15	15	15	15
(3) Sum of (1) and (2) °F	44	47	51	55	55	55	55	55	55	55	55	55

C. <u>Dew Points Prior to PMP Storm</u>

	Hours Prior to Storm											
	6	12	18	24	30	36	42	48	54	60	66	72
(1) Difference between dew point at beginning of storm and at indicated times prior to storm (Figure 15.13) °F	0	1	1	1	2	2	2	3	3	3	4	4
(2) = B(1) - C(1) °F	44	47	51	55	55	55	55	55	55	55	55	55

D. <u>Winds During PMP Storm</u>

(1) Basin average elevation: 7000 feet. Basin average pressure (Figure 15.33): 775 mb.

(2-b) 6-hour January anemometer-level winds at 775 mb. (Figure 15.17): 45 kts.

(3) May 6-hour percentage of January wind (Figure 15.15): 69%

(4) Wind of D(2-b) x percent of D(3) = 31 kts.

	6-hour period											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
(5) Duration factor for each 6-hour period (Figure 15.16 and p. 102)	1.00	.93	.87	.83	.77	.73	.69	.66	.64	.61	.59	.57
(6) Anemometer winds in descending order D(4) x D(5) kts.	31	29	27	26	24	23	21	20	20	19	18	18
(7) Windspeeds rearranged after PMP sequence (a) of Figure 15.12. Kts.	20	21	24	27	31	29	26	23	20	19	18	18

E. <u>Winds Prior to PMP Storm</u>

Lowest windspeed during mid-May PMP storm period over Blackfoot Basin is 18 kts. from D (6). This value continues for 72 hours prior to beginning of storm.